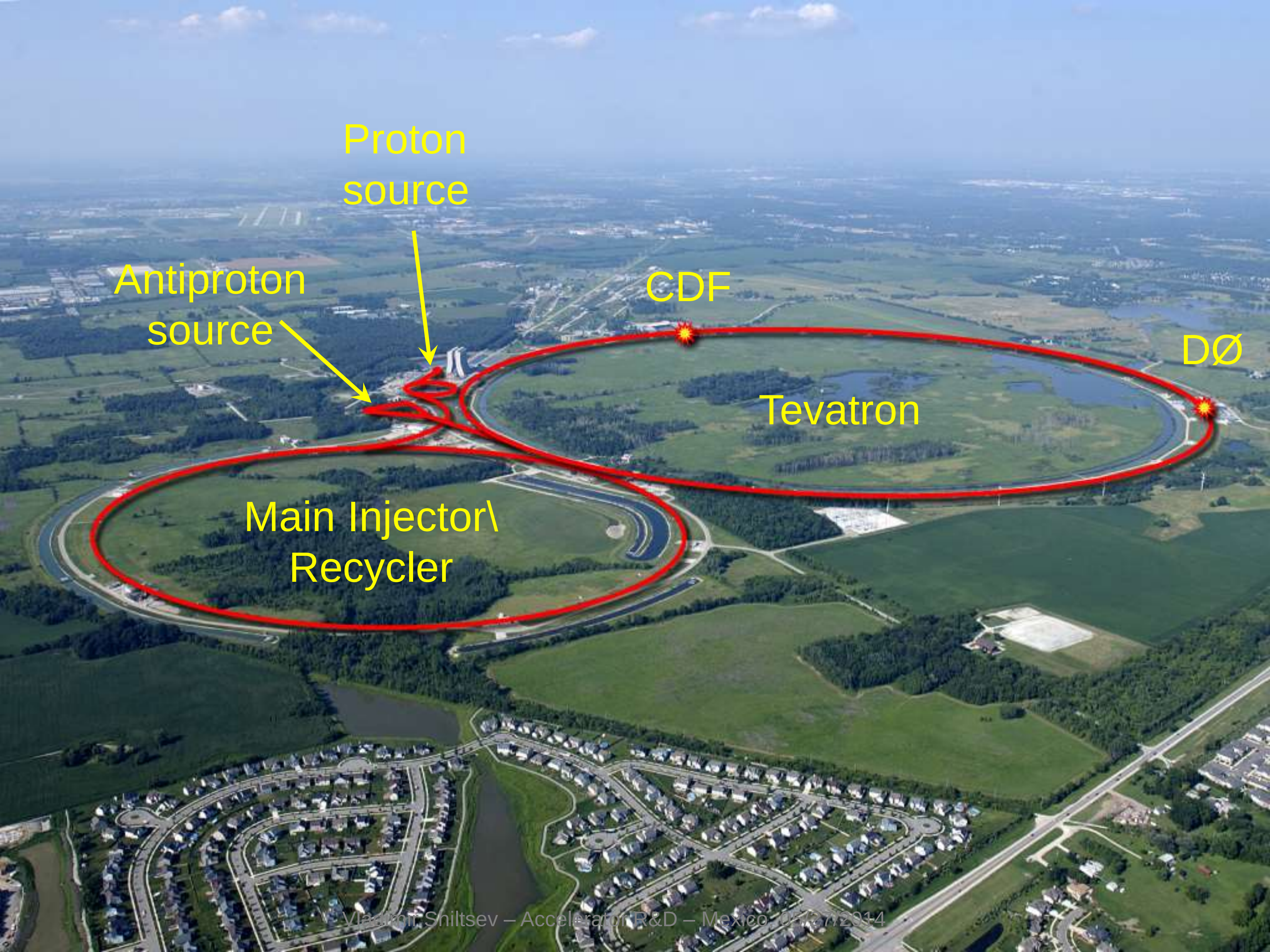

Proton
source
Antiproton
source
CDF
DØ
Tevatron
Main Injector\
Recycler

Challenges and Opportunities in Particle Accelerator Science and Technology

Vladimir SHILTSEV

Director, Accelerator Physics Center

FERMILAB

Reunión Anual de la División de Partículas y Campos de la SMF

26-28 May 2014

Unidad de seminarios Ignacio Chávez

НГУ

Fermi National Accelerator Laboratory – US DOE

- ~1800 staff
- ~$360M annual budget
- ~4200 users incl.1000 foreign (34 states)
- 27.5 км^2 site, near Chicago

- The highest energy beams (till 2010 → LHC)
- World's most powerful neutrino beam, astrophysics experiments, theory
- 2 out of 6 quarks discovered at Fermilab

FNAL – established 1967

Technologist

Fermilab Organization Structure

- **Particle Physics Division:** runs experimental physics projects (neutrino program, CMS at CERN, etc), theoretical physics/astrophysics departments
- **Accelerator Division:** provid beams for basic research
- **Accelerator Physics Center:** methods and accelerator techn
- **Technical Division:** provides perform R&D in superconduc radio frequency cavities
- **Computing Division:** develops computing facilities for the Laboratory research programs

Accelerators and Beams

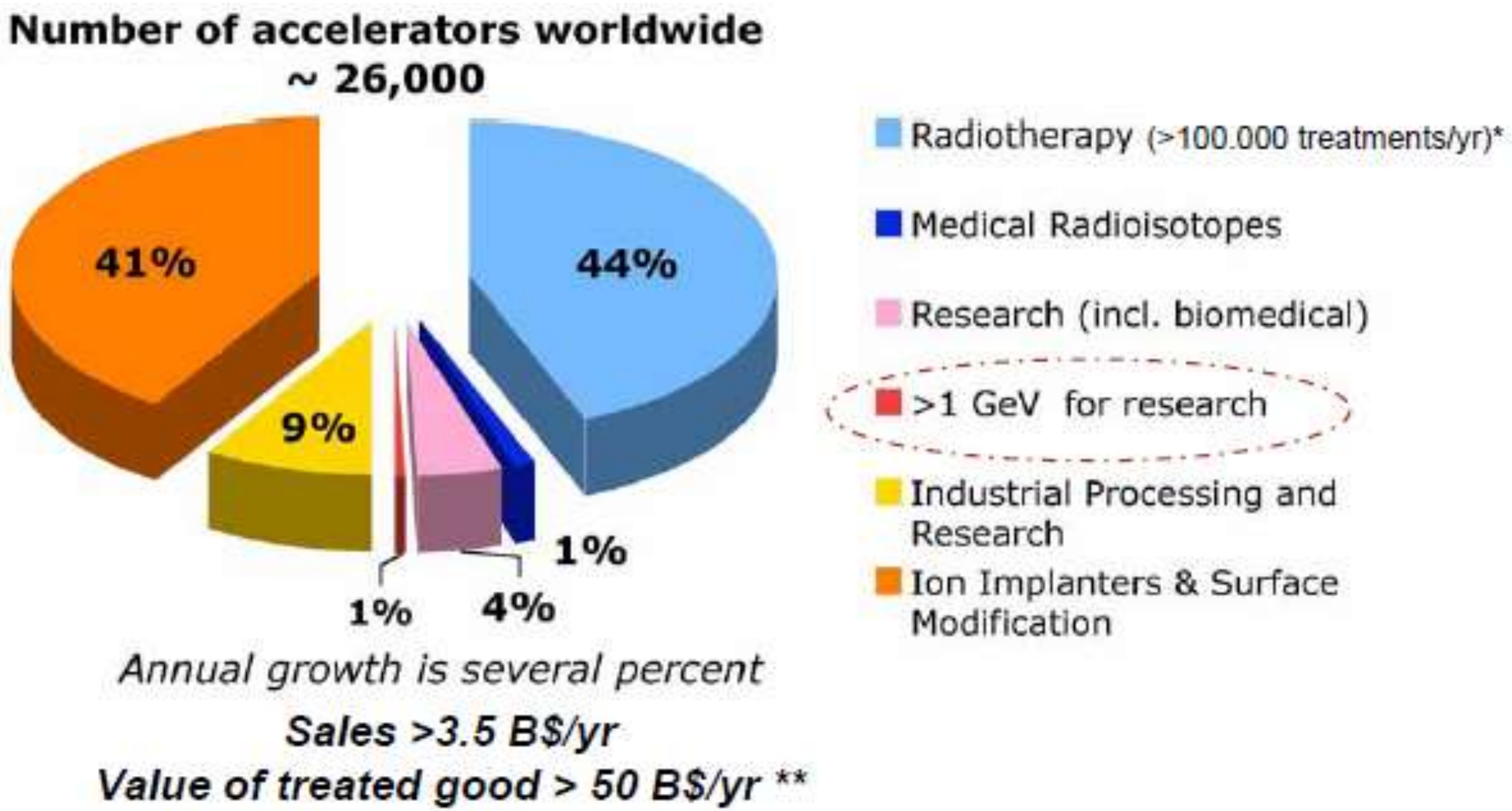
- What are they for?
- Types & how they work?
- What's their future?
- Main challenges
- Opportunities for research
  - For you ! + at Fermilab!

What are they for

Beams of charged particles offer high(est) energies, highly concentrated power and good control of it. So, main uses of beams are driven by their:

- High energy E
- High power $P=E\times I$
- Applications E, P or $L=P/size^2$

Applications of Accelerators



Research Machines: Just the Tip of the Iceberg

Example: Spallation Neutron Source (Oak Ridge, TN)

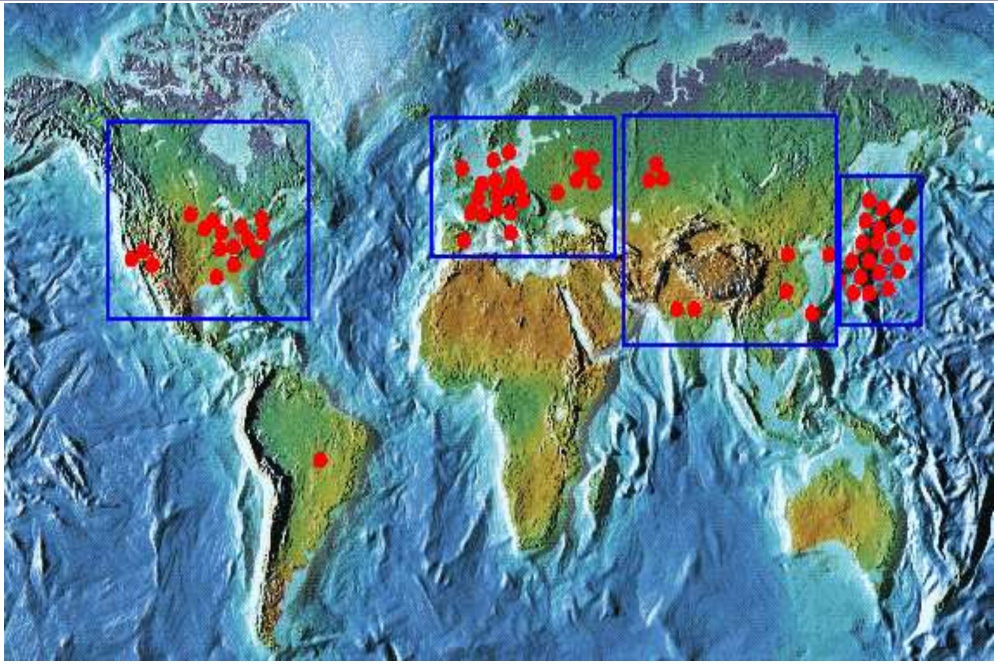
A 1 GeV Linac will load 1.5E14 protons into a non-accelerating synchrotron ring.

These are fast extracted onto a Mercury target

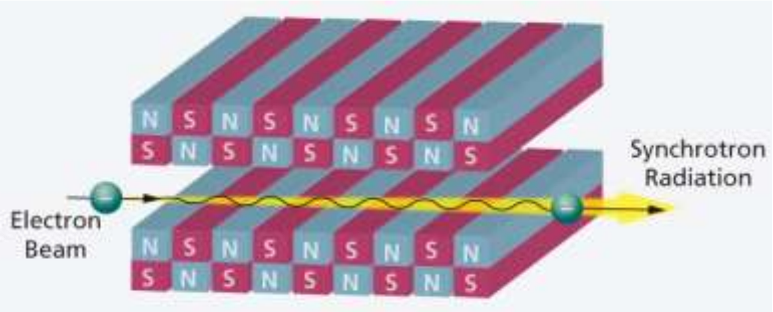
This happens at 60 Hz -> 1.4 MW

Neutrons are used for biophysics, materials science, industry, etc…

Light sources: too many to count



- Put circulating electron beam through an "undulator" to create synchrotron radiation (typically X-ray)
- Many applications in biophysics, materials science, industry.
- New proposed machines will use very short bunches to create coherent light.



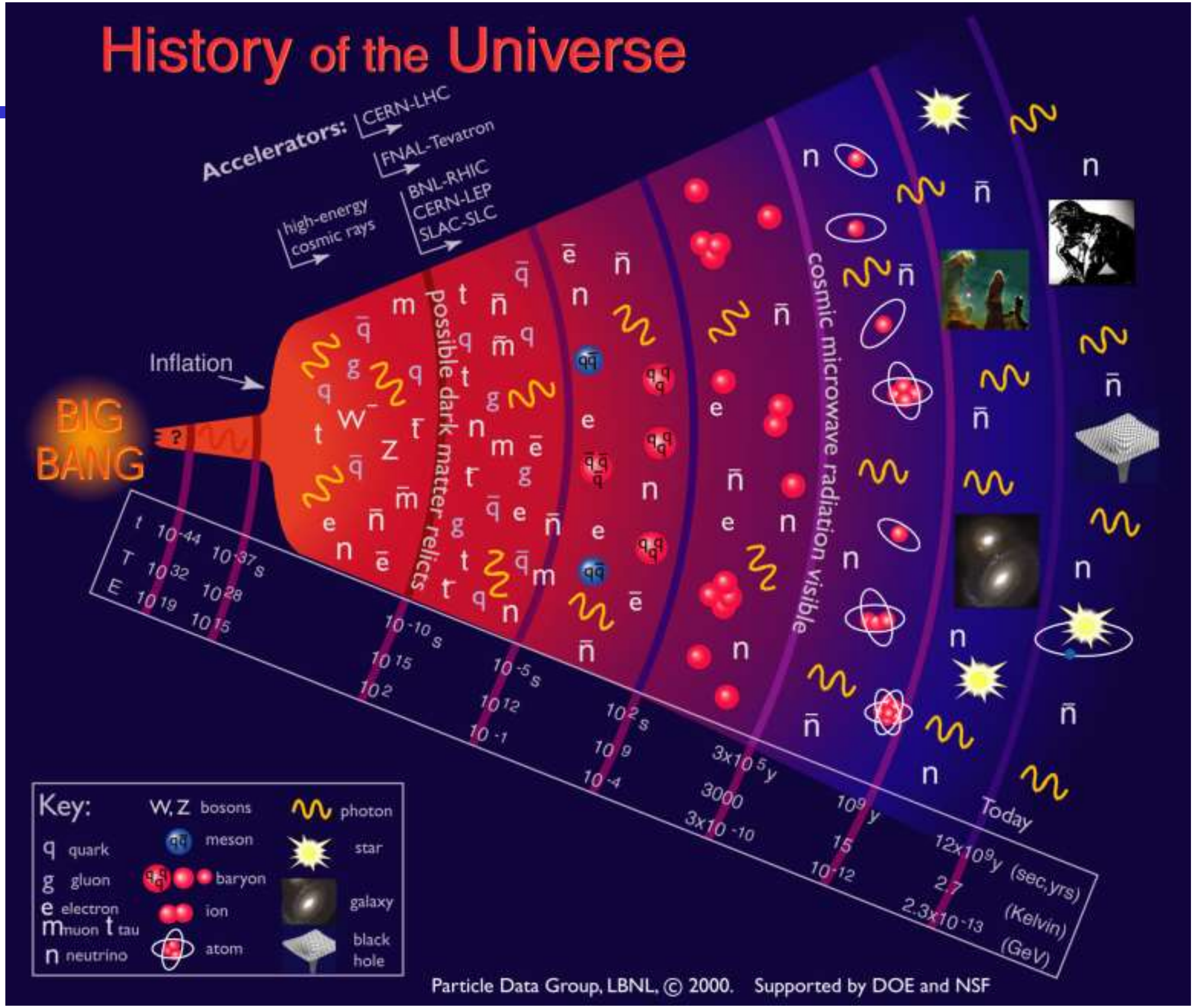
Thrust for High Energy: Physics

- To probe smaller scales, we must go to higher energy

~size of proton

$$\lambda = \frac{h}{p} \approx \frac{(1.2\,\mathrm{fm})}{p\,(\mathrm{in\ GeV/c})}$$

- To discover new particles, we need enough energy available to create them
- The rarer a process is, the more collisions per unit area (luminosity) we need to observe it.



We're currently probing down to a few picoseconds after the Big Bang

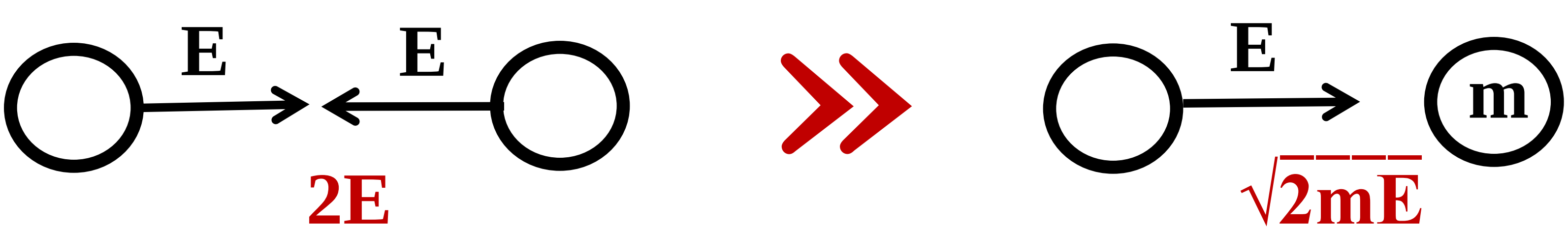
Accelerators - Colliders

Invented in 1956 (if not earlier)

First operational in 1964 (~50 years ago)

"…It is estimated that [since then] accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years. " Haussecker&Chao *Physics in Perspective* 13 146 (2011)

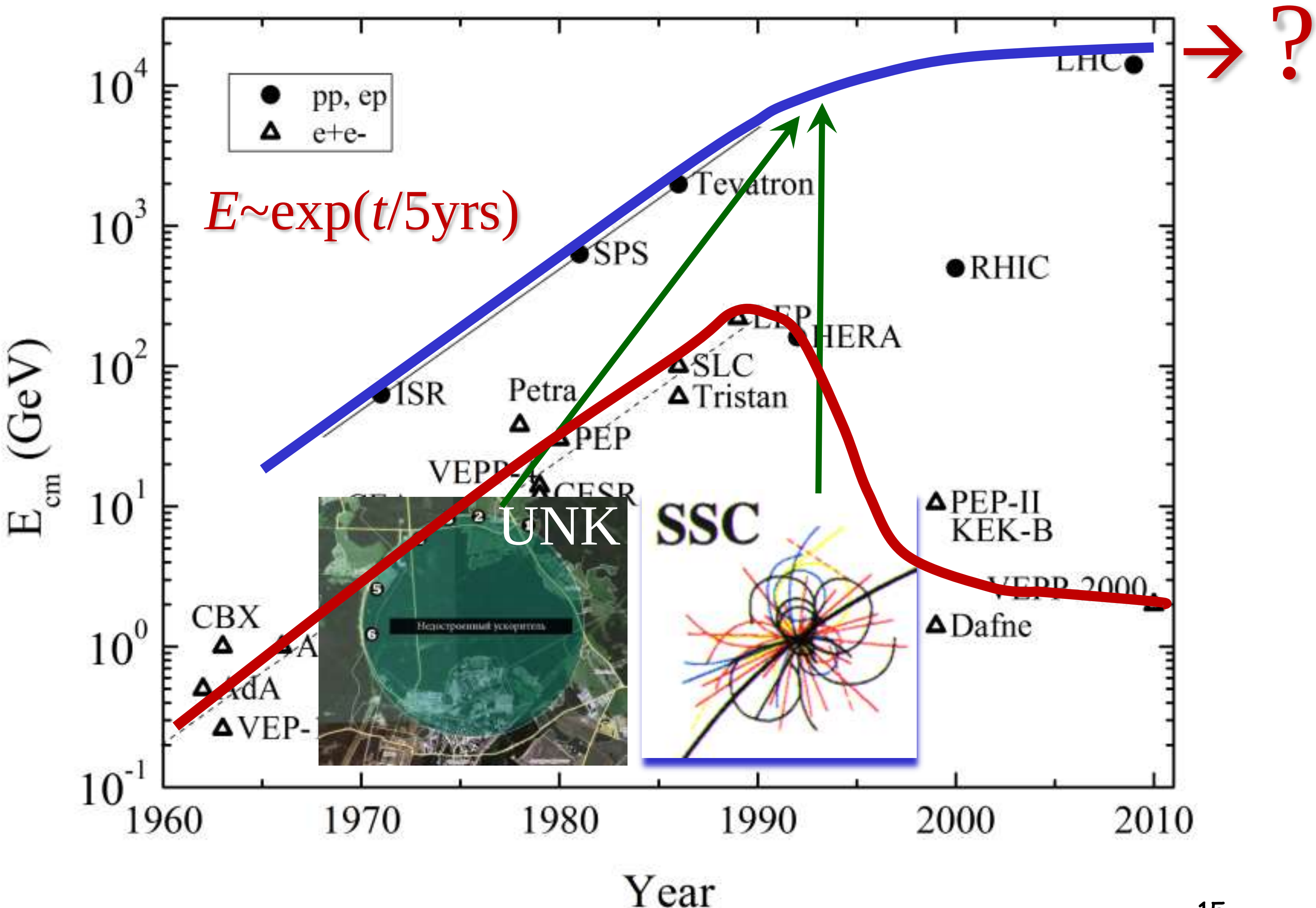
The (only) reason is ENERGY



29 Built… 6(7) in Operation Now

LHC	pp	14 TeV	L=1e34
RHIC	pp	250GeV	L=2e32
KEKB	ee	4+7GeV	L=2e34
VEPP4	ee	7GeV	L=4e30
BEPCII	ee	4GeV	L=1e33
VEPP2000		1-2GeV	L=1e31
DAFNE	ee	1GeV	L=4e32

Colliders: Glorious Past



Progress and Future of Accelerators (Coll

depends on technology (>1)

Sci'sts/Ops

Vacuum/Cryo

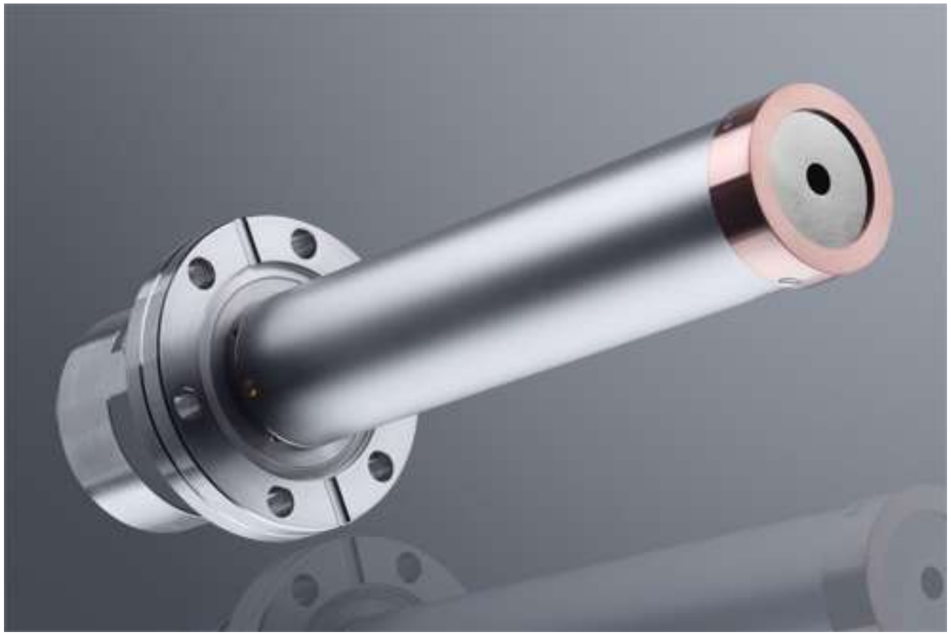
Magnets

Accelerating systems

Sources of particles

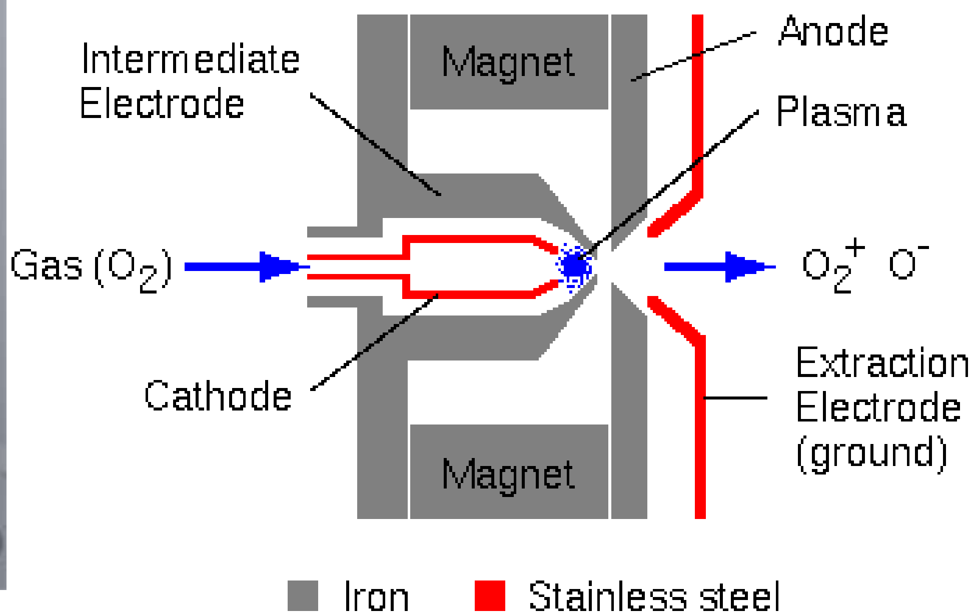
Particle Sources

electrons



Ions/protons

Duoplasmatron

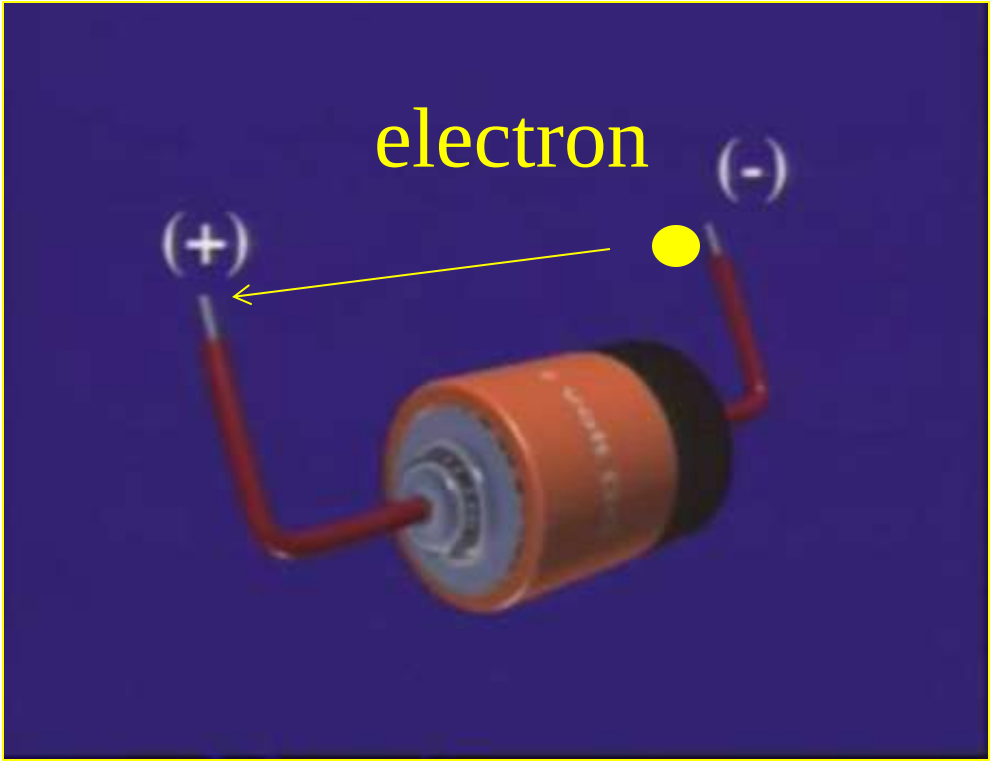


Challenge #1: It's much harder to make so-called secondary particles – positrons, muons, antiprotons, etc

Challenge #2: High brightness (current/phase space area) beams in demanding time formats

Accelerating elements: DC

AA Battery

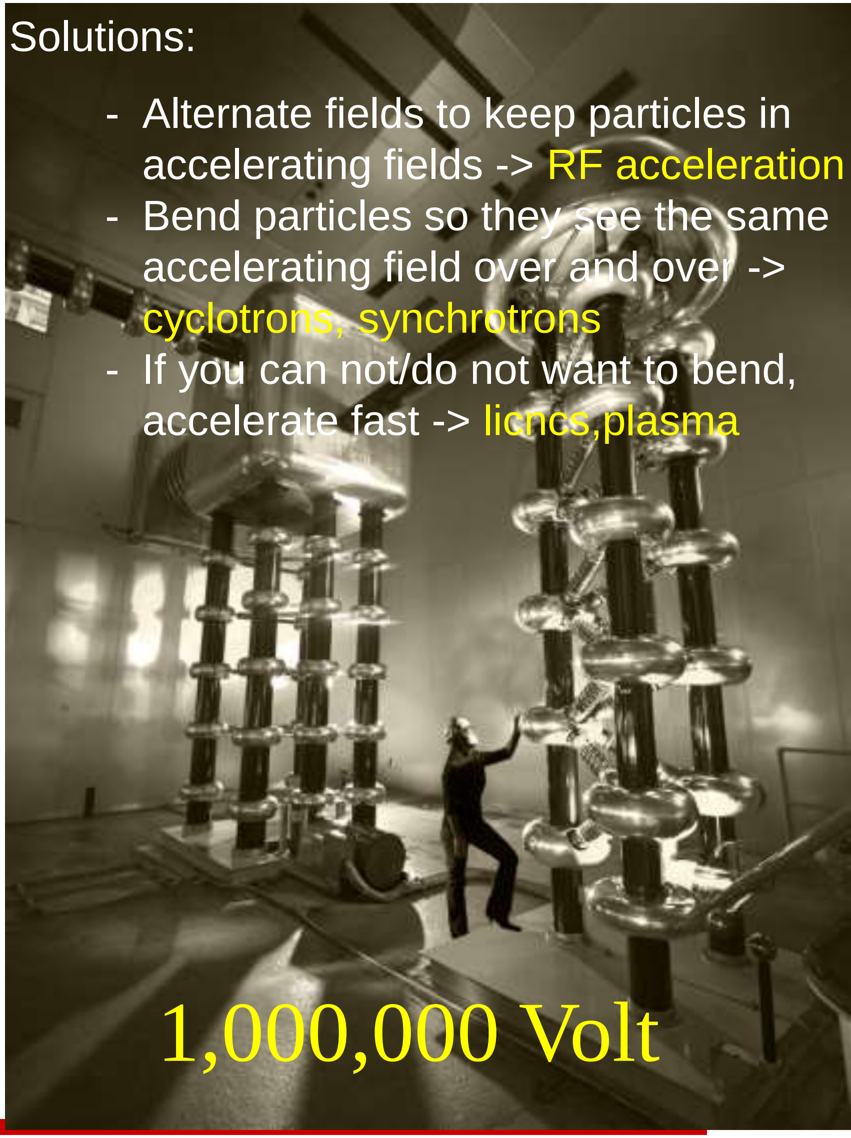


1 electron x 1 Volt

=1 electron Volt

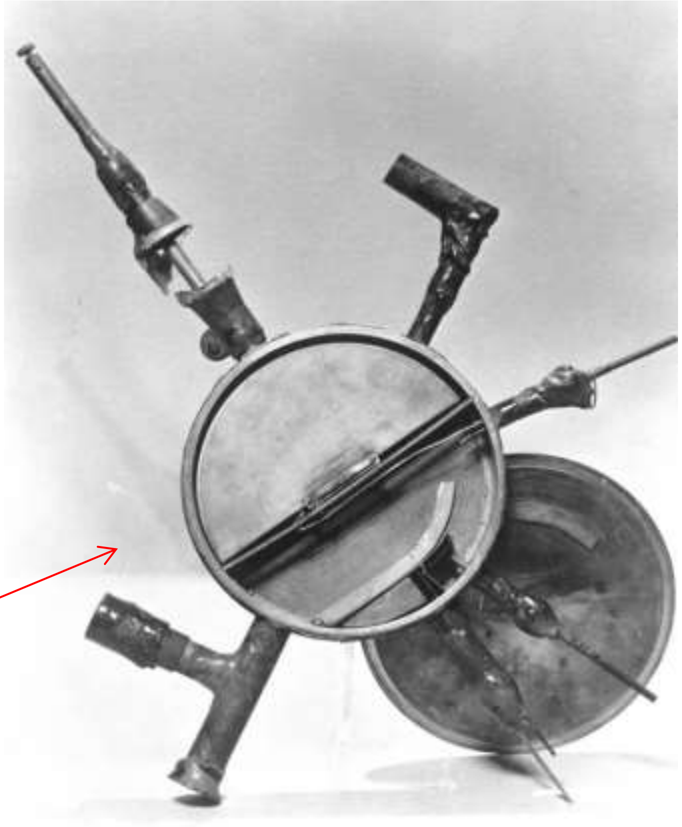
Solutions:

- Alternate fields to keep particles in accelerating fields -> RF acceleration
- Bend particles so they see the same accelerating field over and over -> cyclotrons, synchrotrons
- If you can not/do not want to bend, accelerate fast -> licncs,plasma



The First Modern Accelerator

Ernest O. Lawrence



Cyclotron 25$

80,000 Volts

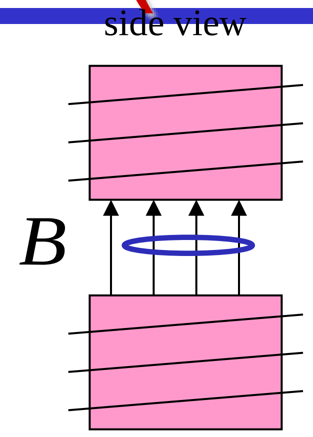
The Cyclotron (1930's)

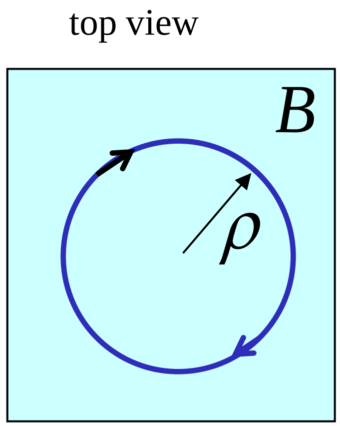
- A charged particle in a uniform magnetic field will follow a circular path of radius

$$\boxed{\begin{aligned} \rho &= \frac{mv}{qB} \\ f &= \frac{v}{2\pi\rho} \\ &= \frac{qB}{2\pi m} \ (\text{constant}‼) \\ \Omega_s &= \frac{f}{2\pi} = \frac{qB}{m} \end{aligned}}$$

"Cyclotron Frequency"

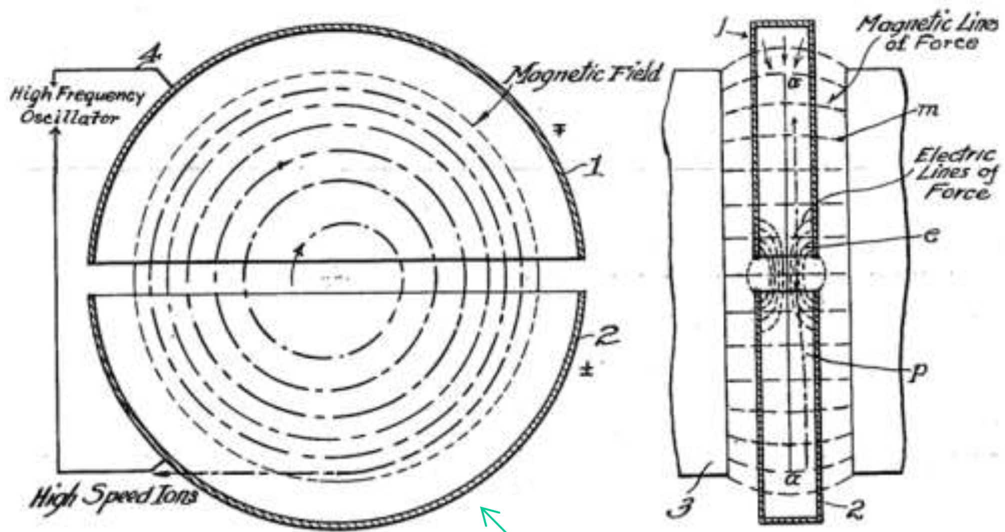
Red box = remember!





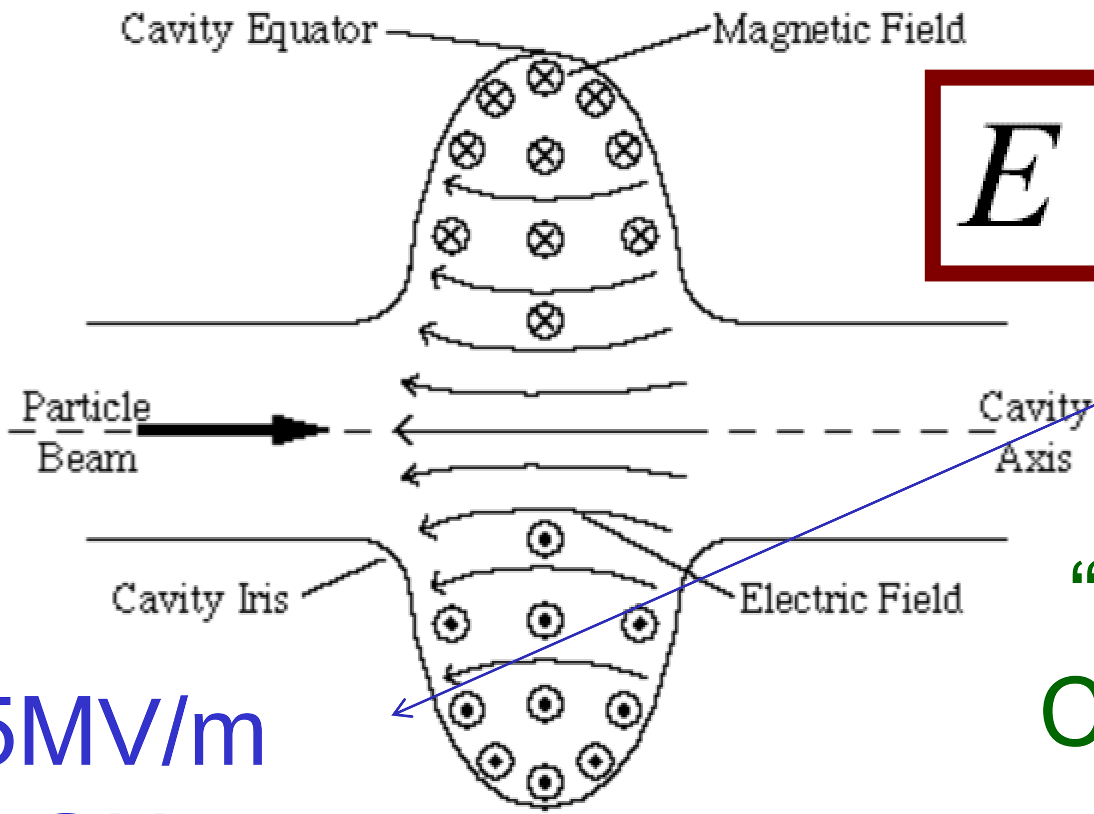
For a proton:

$$f_C = 15.2 \times B[T] \ \text{MHz}$$



Accelerating "DEES"

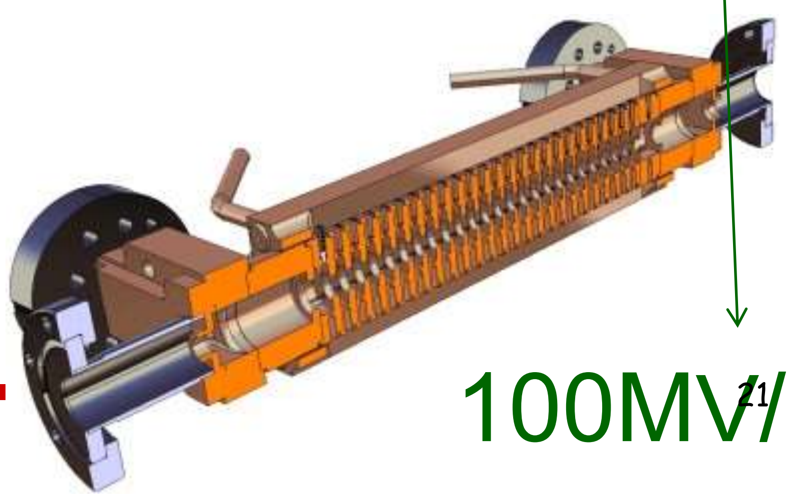
Present Acceleration Technologies



$$E = eGl$$

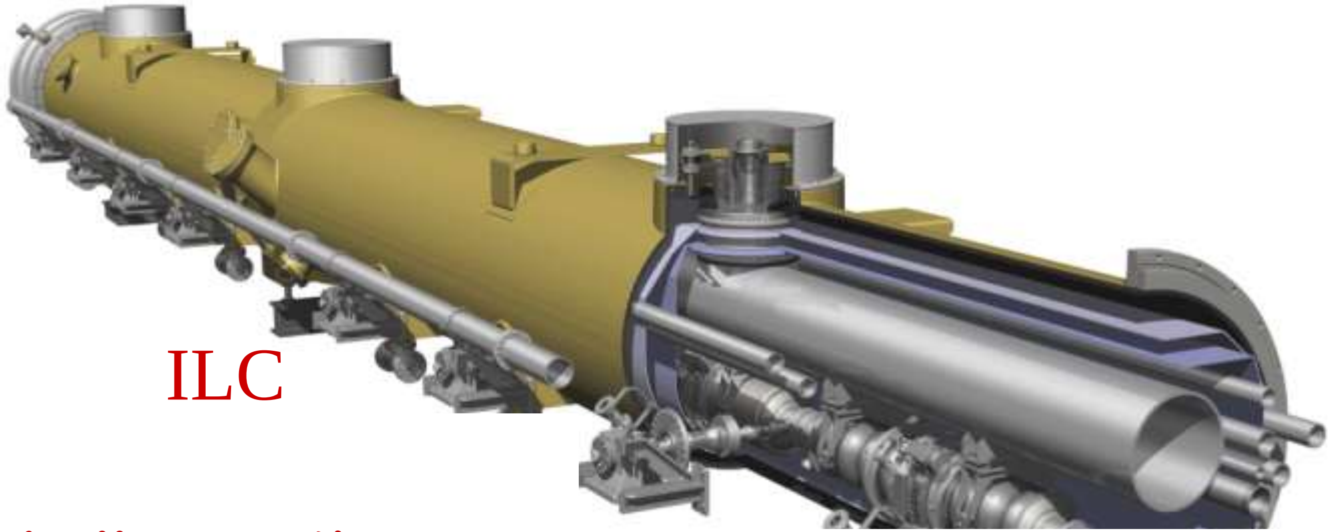
SRF 35MV/m
Nb, 1.3 GHz

"Warm RF"
Cu, 12 GHz



100MV/m

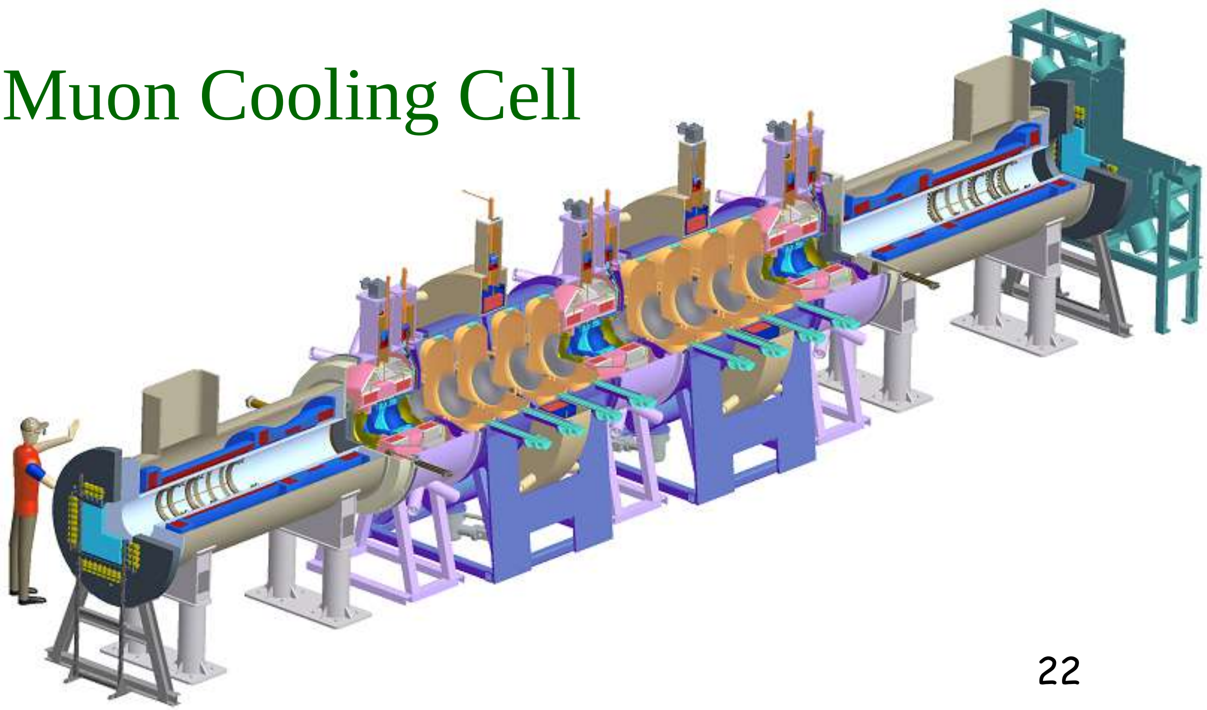
Radio Frequency Accelerator Cavities



ILC

Challenge #2:
Cost-cost-cost!
per GeV
per MW
per year of ops

Challenge #1:
Highest gradients
& most efficient
energy transfer
to the beams



Muon Cooling Cell

Magnets *(in the Tevatron Tunnel)*

Accelerator SC Magnets

Challenges: maximize B-field, minimize cost

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

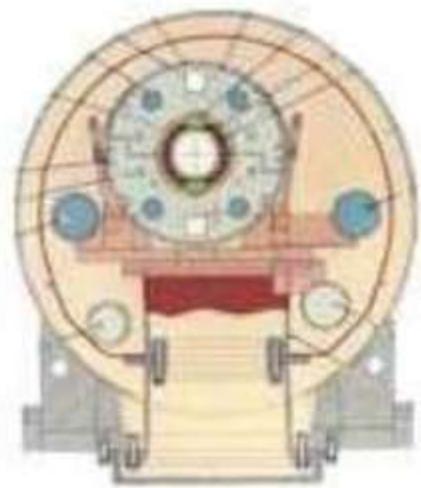
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

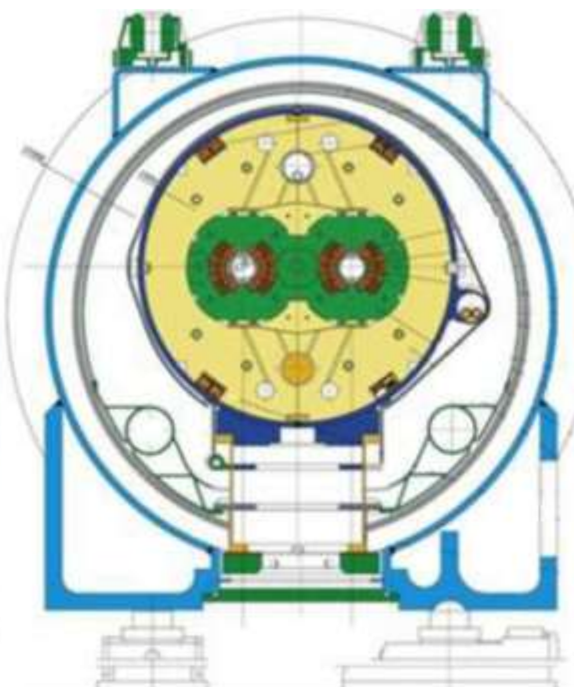
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

LHC,
15 m, 56 mm
1276 dipoles



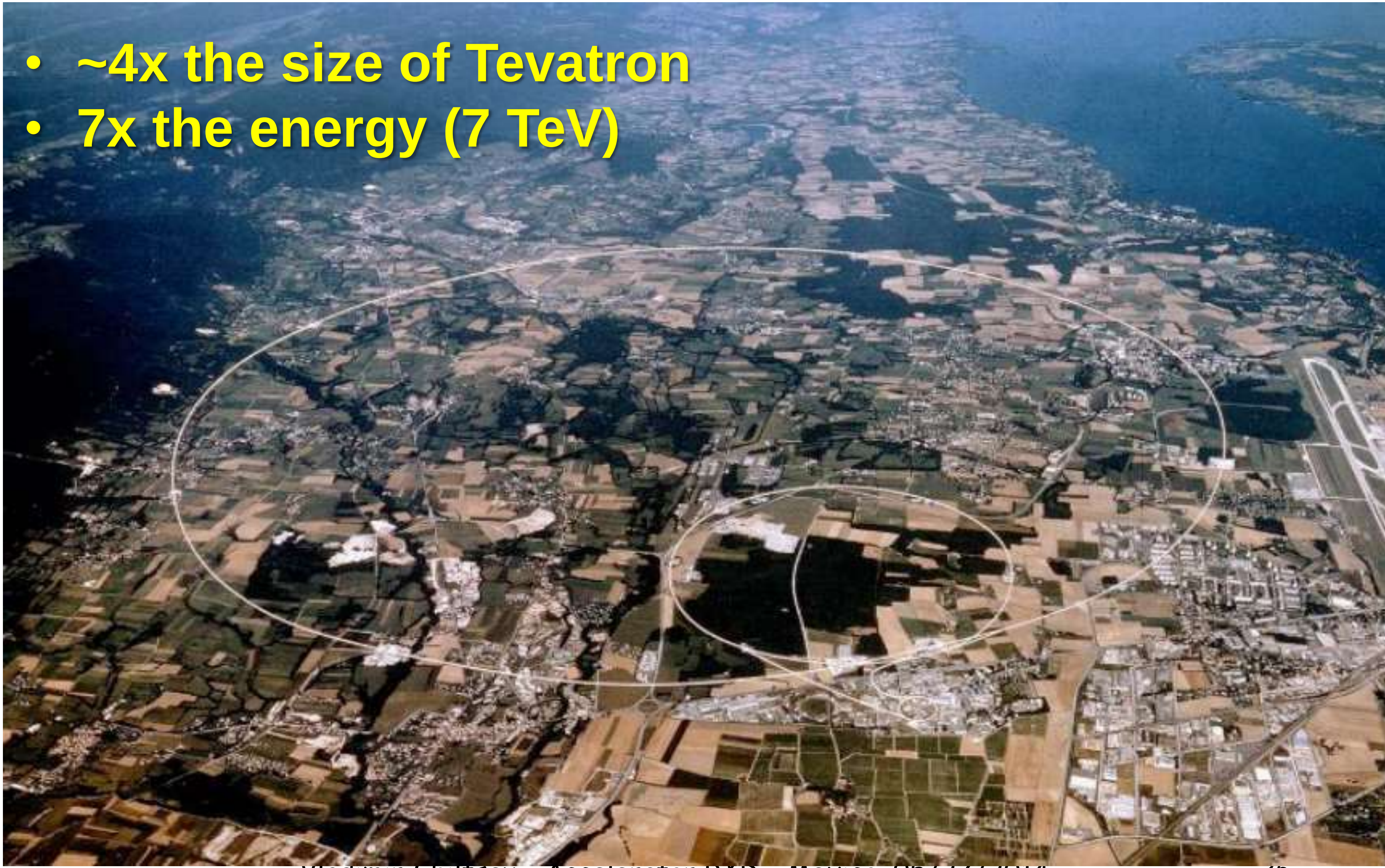
NbTi cable
2K He
two bores

Fermilab's Tevatron – 6.3km

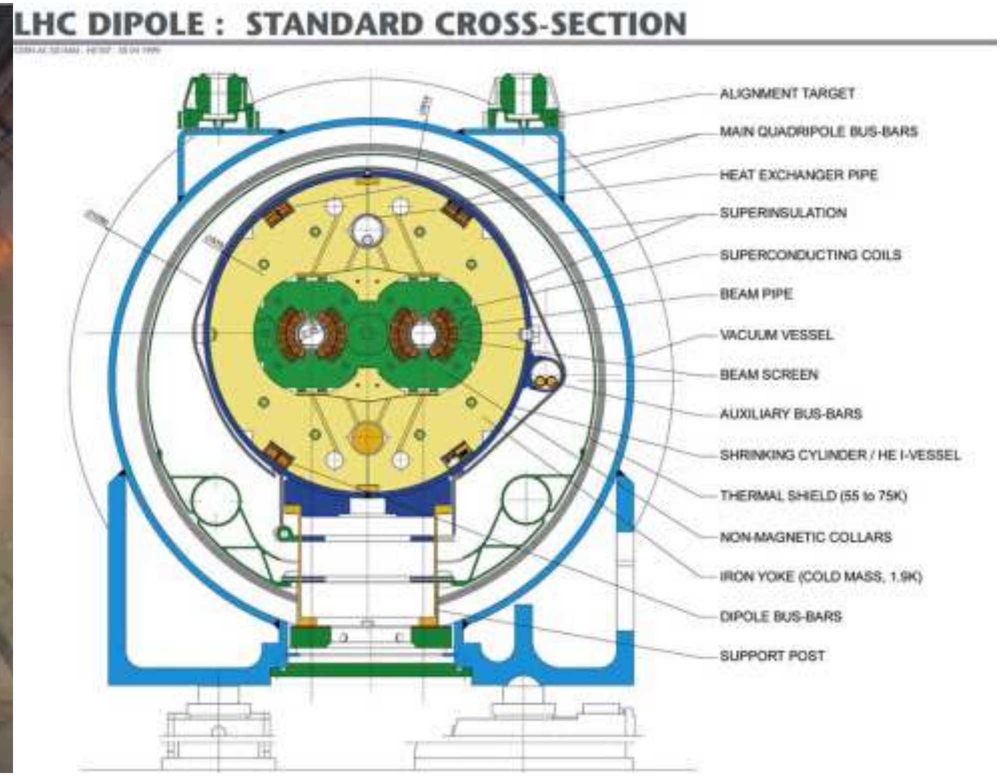
1,000,000,000,000 (12 zeroes!) Volt

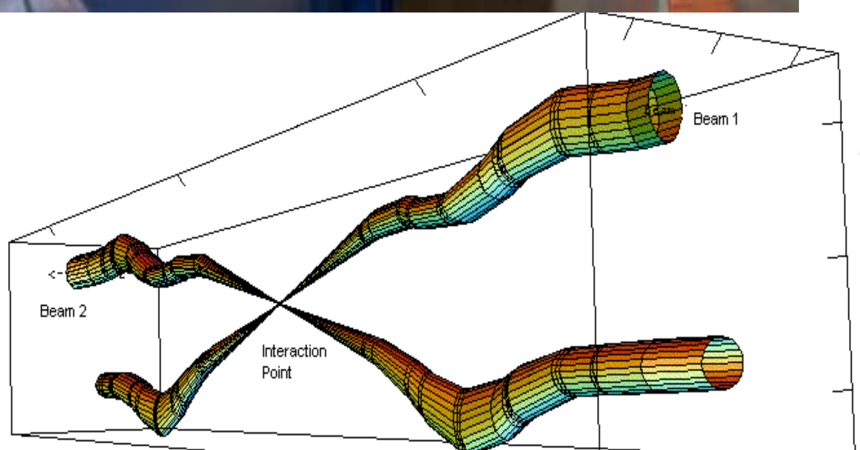
LHC (Large Hadron Collider) 27km

- ~4x the size of Tevatron
- 7x the energy (7 TeV)



Inside the LHC tunnel





Relative beam sizes around IP1 (Atlas) in collision

1232 bending magnets 15м

NbTi cables, 13 кA@1.9 K

~ 9 Tesla (90 000 G), 10 GJ

Beampipe vacuum <1e-12 atm

LHC = “big and long vessel”

Quench Example: MRI Magnet*

*pulled off the web. We recover our Helium.

Suggestion for LHC Startup 2015:
invite Curandera & do *Limpia*

the scent of herbal smoke comes from censers which the *Curanderos* swing around their patients in a cleansing ritual known as *Limpia*. The practice has been around for quite some time now – at least since 500 BC.

People

Scientists, Engineers, Technicians, Operators

Big accelerators are very sophisticated devices, require experienced staff to operate, maintain, improve, upgrade:

- Tevatron ~500 people
- LHC ~800 people

Accelerators for HEP (2030+)

- LHC *pp* → high-luminosity LHC (x5 design *L*,~2025)
- FNAL Main Injector *p* → double intensity for neutrino program (at ~120GeV PIP-II SRF linac, ~2025)
- KEKSuper-B factory *e+e-* → *L~8e35*, 4+11GeV,~2018
- Factories:
  - Neutrino factory
  - Higgs: an, SC RF)
  - Higgs: *y or e-p*
- Energy
  - *e+e-* (*3 TeV)*
  - (unpr future)
- Energy
  - *pp* (100 TeV FCC@CERN)

Depend on:

i. LHC results

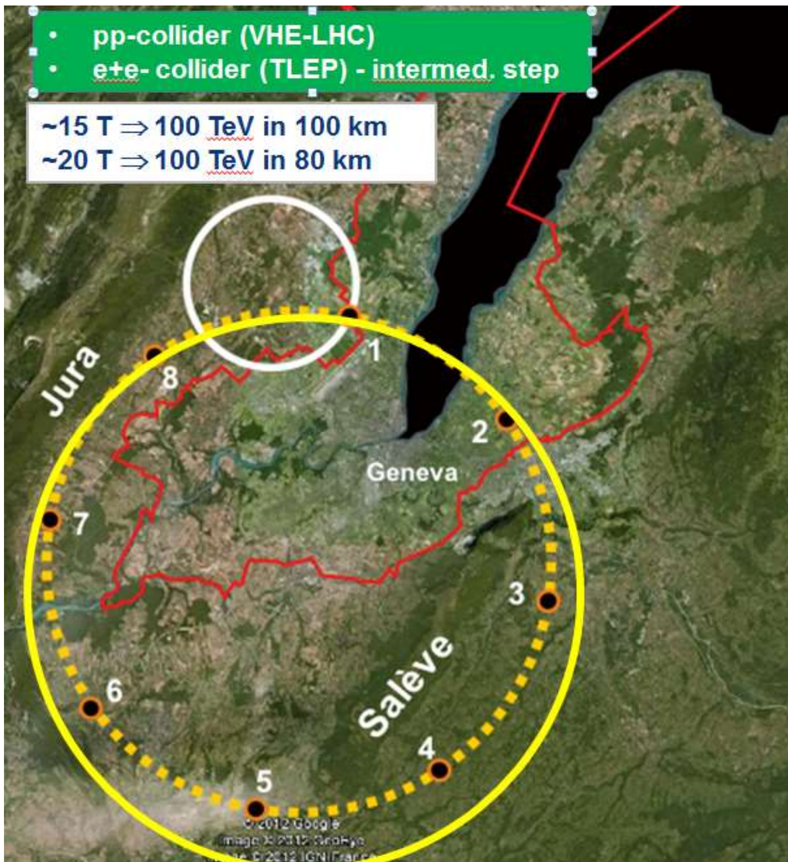
ii. (Cost/Performance)

iii. Feasibility

→ Need R&D: Example

- **100 km 100 TeV p-p collider**

(Future Circular Collider)



- **100 km tunnel**
  - *3-4 times LHC*
- **100 TeV -SC magnets**
  - *6 times LHC*
- **400 MW infrastructure**
  - *3x LHC*

If built "as LHC" (no R&D)

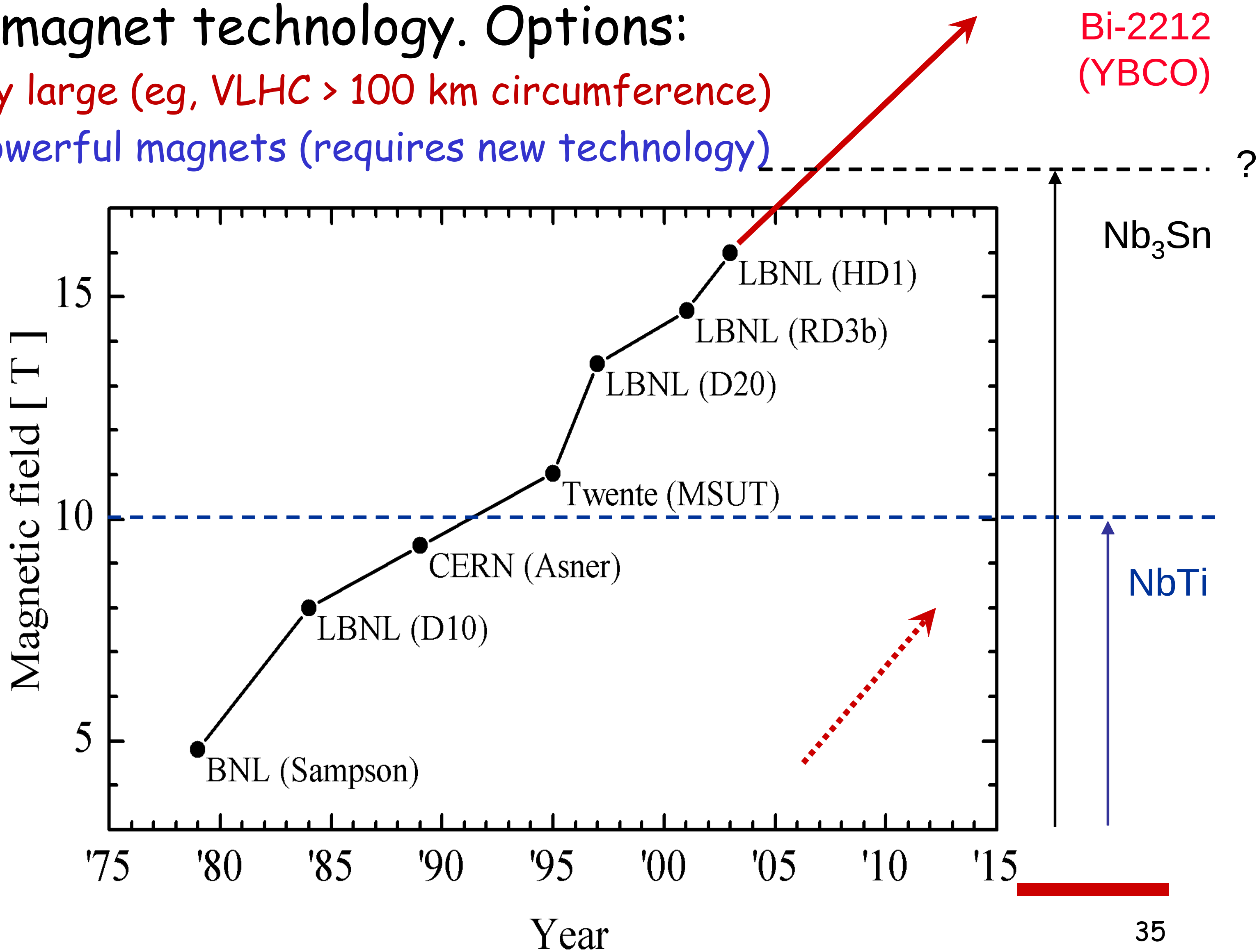
- *Cost will be ~3x LHC*
- ***30B$? 20 years?***

Opportunities at Fermilab

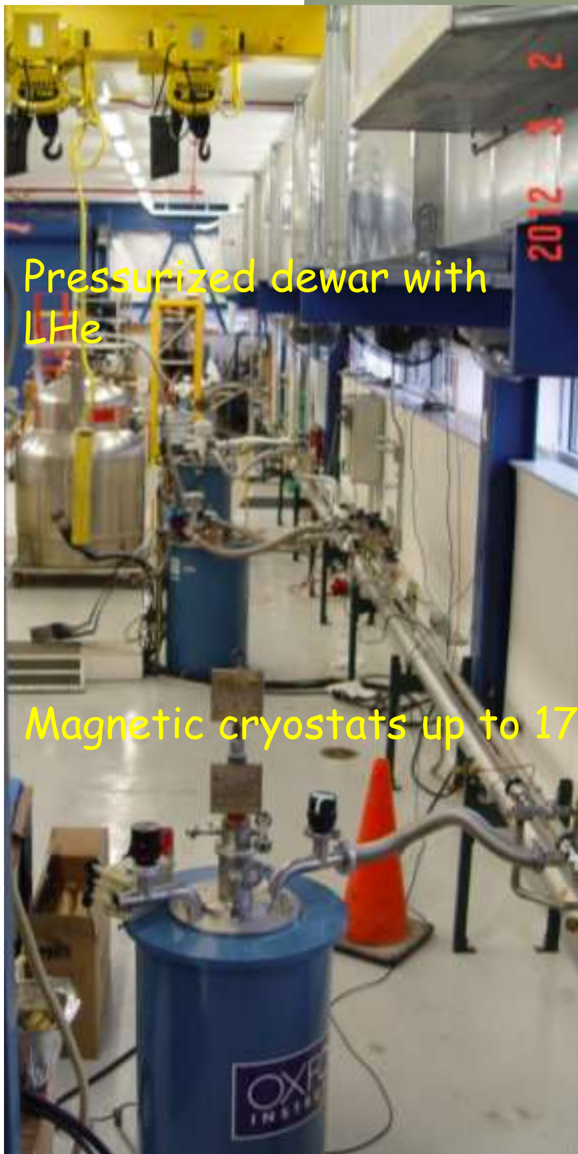
- Accelerator Technology
  - Superconducting Magnets
  - Normalconducting magnets
  - Superconducting RF caities
  - Normalconducting RF cavities
  - High power targets
  - Beam diagnostics, controls and instrumentation
- Accelerator Science
  - Beam focusing optics
  - Beam dynamics, instabilities
  - Collimation
  - Beam sources
  - New acceleration techniques, new materials
- Facilities
  - Test stands, beam facilities

Superconducting Magnets?

- The energy of Hadron colliders is limited by feasible size and magnet technology. Options:
  - Get very large (eg, VLHC > 100 km circumference)
  - More powerful magnets (requires new technology)

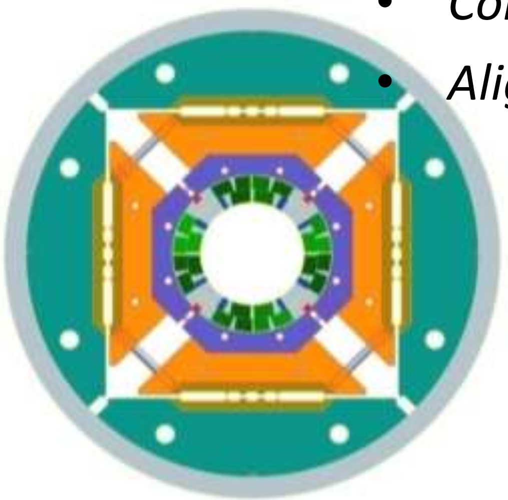


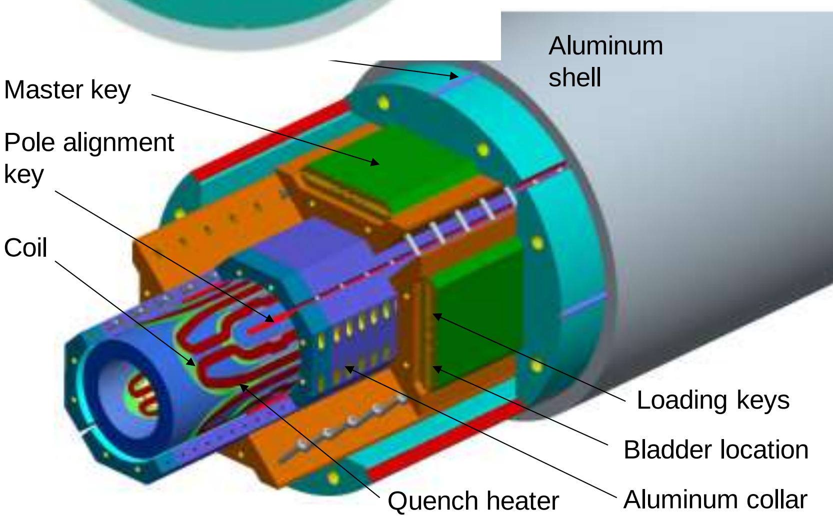
Superconducting R&D Lab

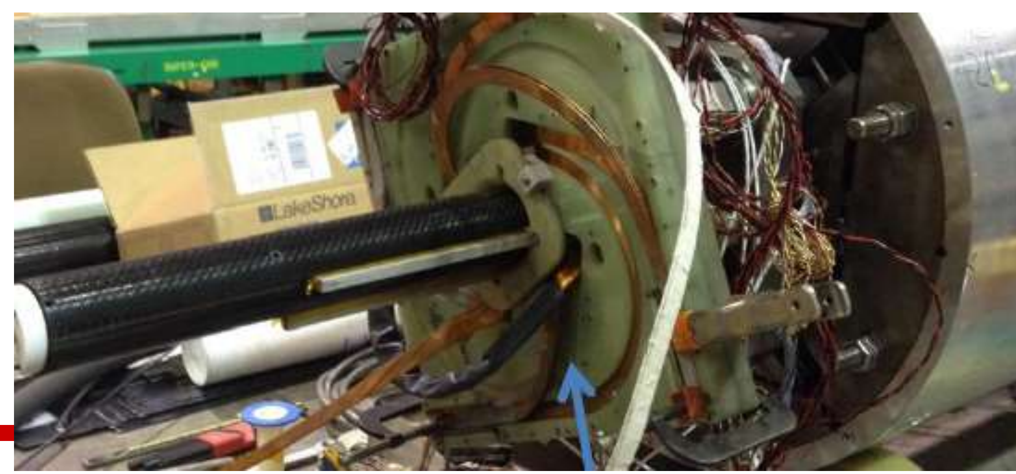


From **NbTi** to **Nb3Sn**: LHC IR Quadrupoles

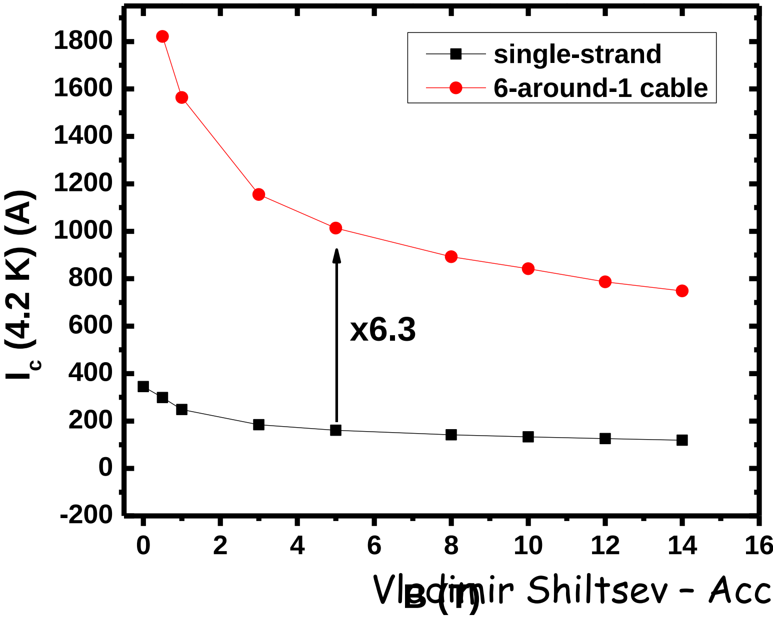
- **<u>Goal</u>: high performance Nb_3Sn IR Quads *for HiLumi - LHC***
- 120 mm aperture, 15 T peak field at 220 T/m (1.9K)
- Main challenge – field quality and stability:
  - *Control of geometric, saturation, magnetization, eddy currents*
  - *Alignment at all stages of coil fabrication, assembly & powering*







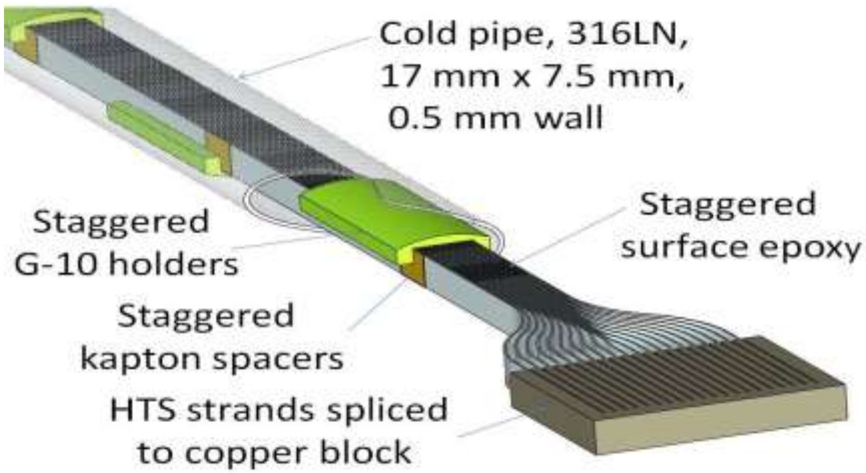
High Field Magnets with HTS

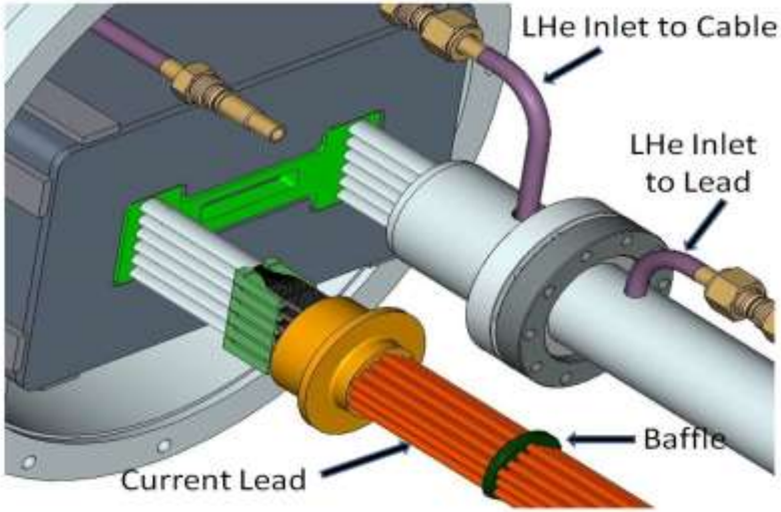


- High Temperature Superconductors can withstand very high fields **(50T?)**
- Demonstrated **15+ T** (16+ T on coil)
  - ~25 mm insert HTS solenoid
  - YBCO "6 around 1" Cable Design
  - Highest field ever in HTS-only solenoid (by a factor of ~1.5)

Developing a test program for operating HTS insert + mid-sert in an external solenoid a >30 T

Fast-Cycling HTS Magnet Design/Constr'n

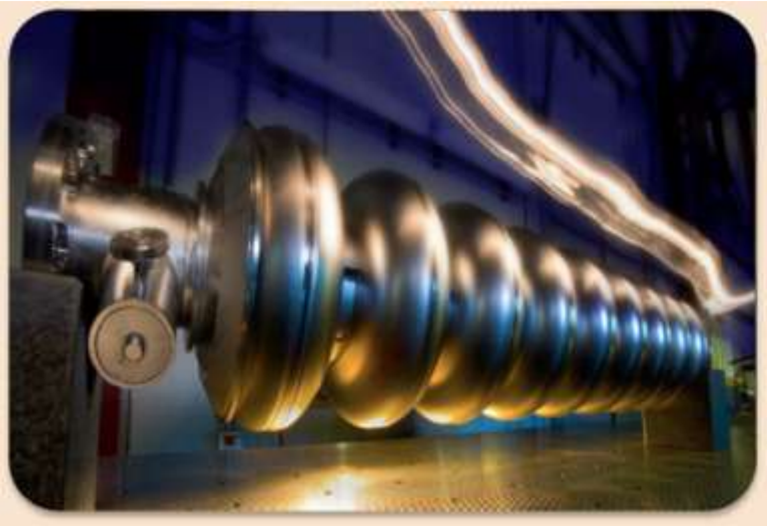




YBCO tape, 20 T/s, low loss (1/10 of LTS), cheap

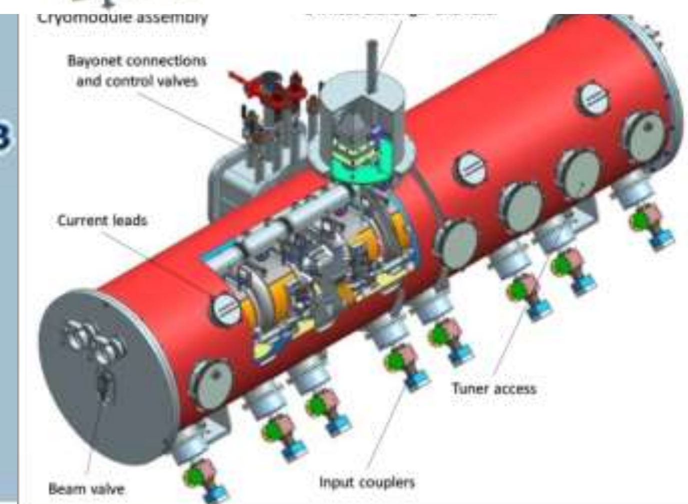
Super-Conducting RF

- Pure Nb
- Main challenges/tasks:
  - High gradient (35MV/m)
  - High Q-factor >1e10
  - Power couplers
  - Phase and amplitude control
  - Better SC materials
- Projects: PIP-II, ILC, LCLS-II



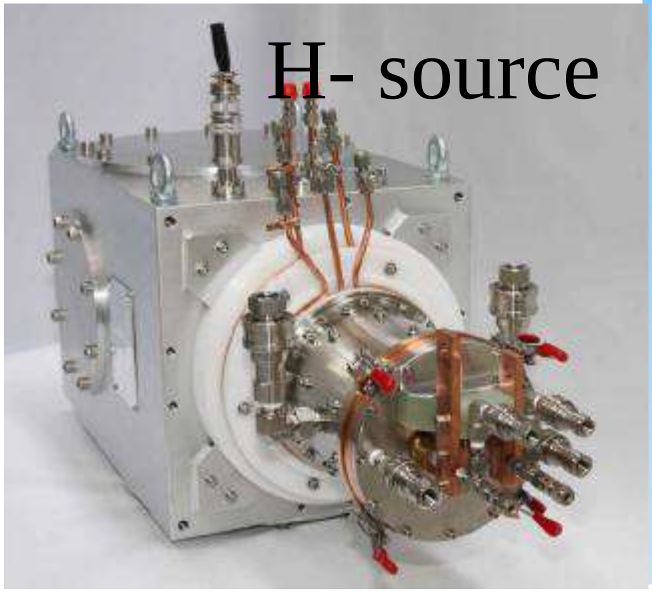
Proton Improvement Plan -II

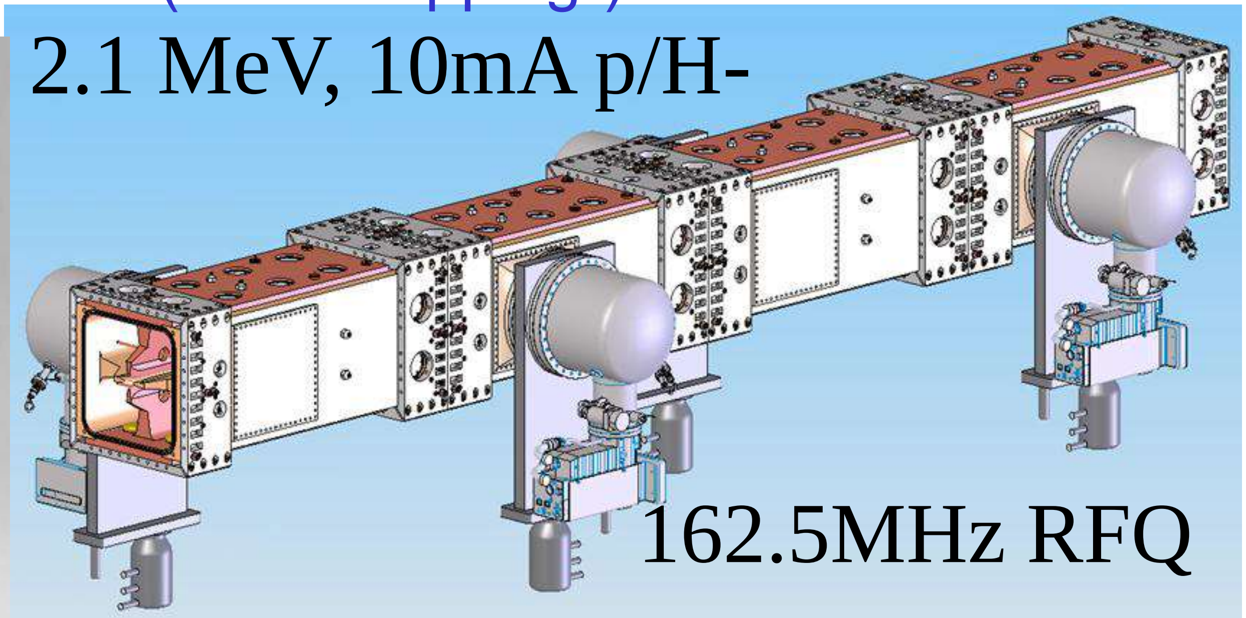
- 1.2 MW proton power on neutrino target
- For LBNF (Long-Baseline Neutrino Facility)
- 800 MeV SC RF Linac: 162→325→650 MHz



R&D for High Power Proton Source

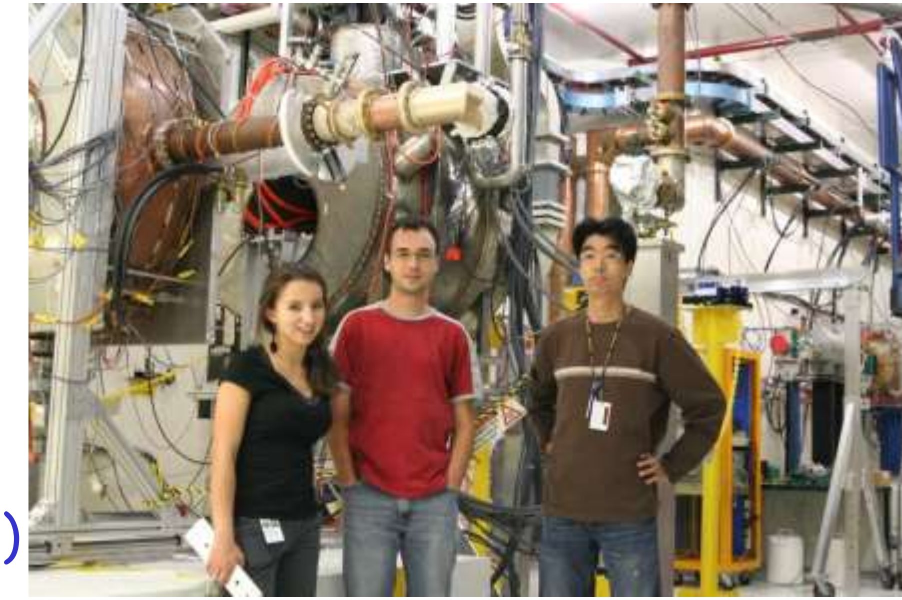
- "Essential R&D towards PIP-II (Proton Improvement Plan) includes Source and 1st stages of acceleration
  - Strongest recommendation by P5 panel, double *p/v* production
- Main challenges/tasks:
  - High current low-velocity beam (space-charge blowup)
  - Proper bunch format (fast "chopping")

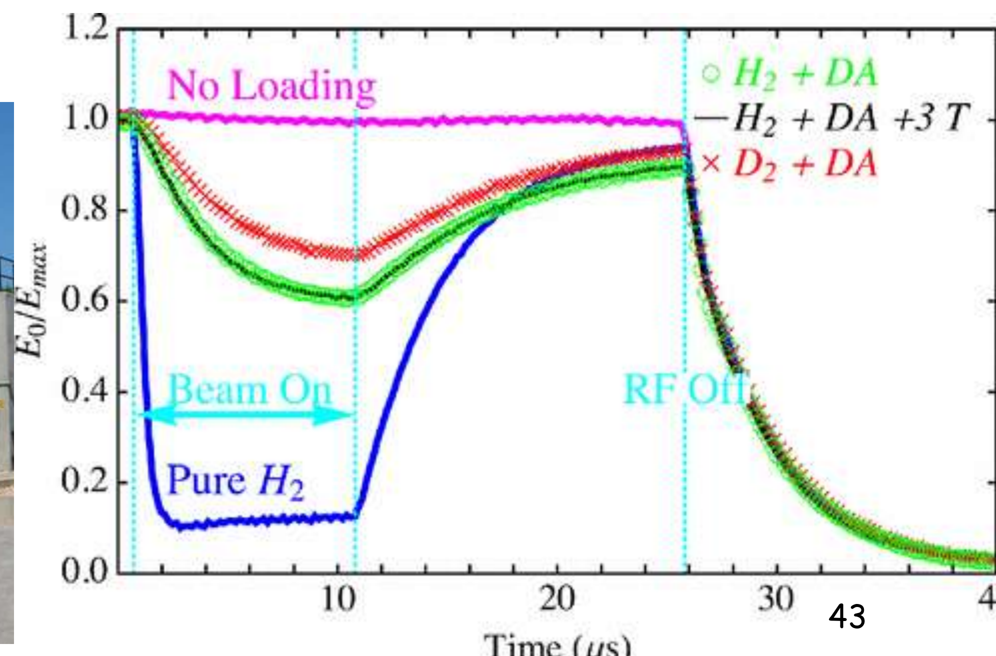




Another R&D: NC RF in B-field

- If strong focusing required:
  - Eg for Neutrino Factory cooling
- 200 MHz or 800 MHZ NC RF cavities in 3-5 T B-field:
  - Sparks lower E-gradient
  - Either cavity coating
  - Or pressurized gas (H2, 100atm)
- MTA Facility with beam



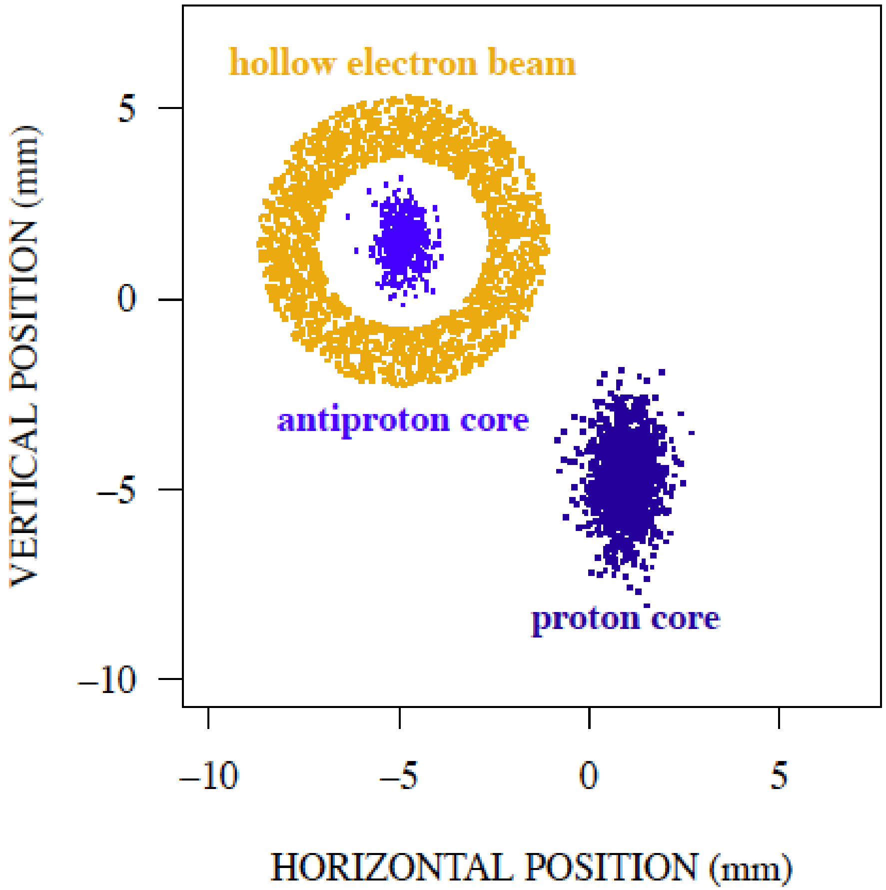


Novel Halo Collimation Methods

Challenge: get rid of unwanted particles without effect on the beam core and no radiation induced

Hollow Electron Beam

Tested in Tevatron

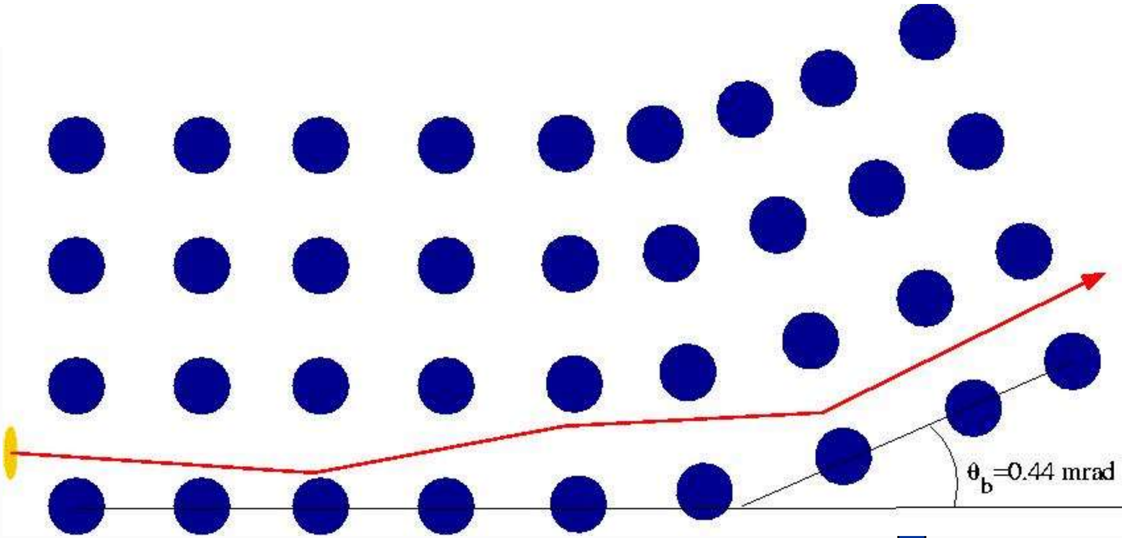


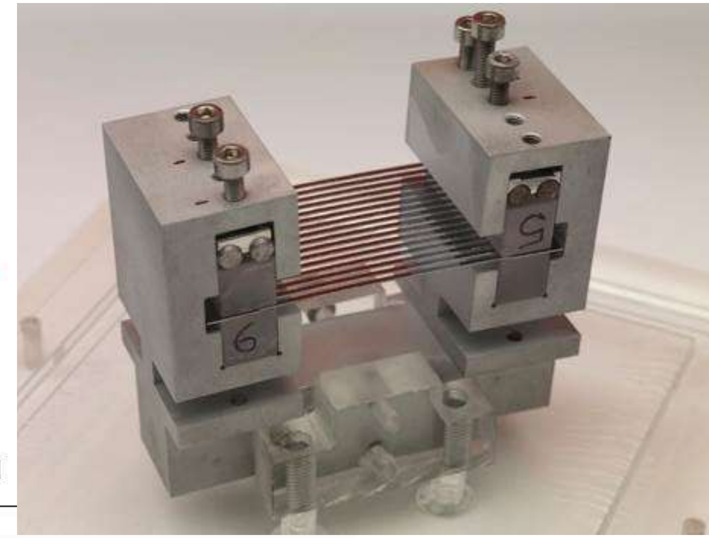
G. Stancari et al., PRL 2011

Tube of electrons (Tevatron electron Lens)
No E-field inside
Strong E-field ouside drives resonances
Fast diffusion = "soft collimator" effect
Cleans close to beam as well (no material)

Now – for the LHC

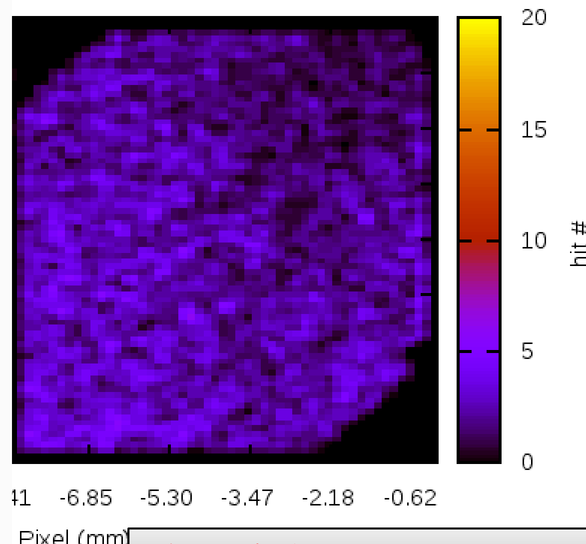
Halo Collimation by Bent Crystals





- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - ➢ deflection/bending (*works*)
  - ➢ focusing (*works*)
  - ➢ acceleration (*if excited*)

N.Mokhov, et al JINST 6 T08005 (2011).

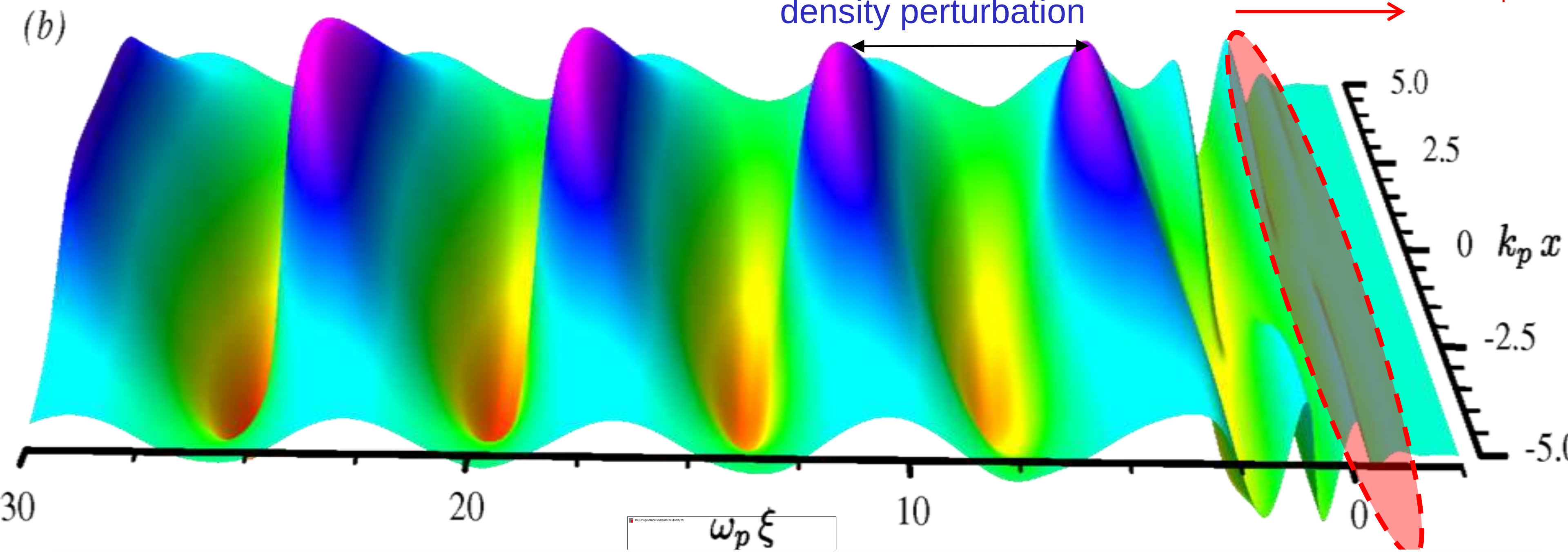


Channeled beam image on pixel detector

T980 Results
D. Still et al. IPAC12

Excitation of Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



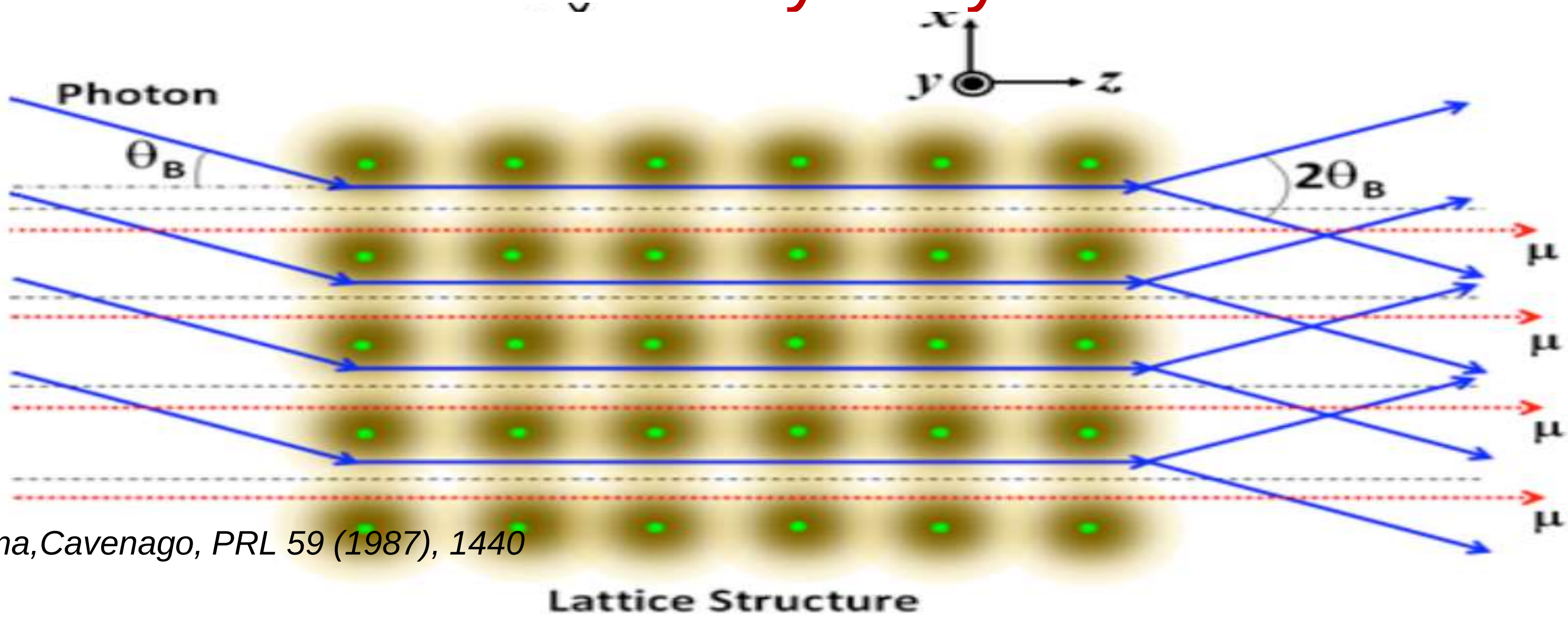
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100\left[\frac{GeV}{m}\right] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:
Short intense laser pulse
$\sim 10^{17} cm^{-3}$, 30 GV/m, $\lambda_p \sim 100\mu$

Option B:
Excite plasma in Crystals
$10^{22} cm^{-3}$, 10 TV/m, $\lambda_p \sim 0.3\mu m$

Field Excitation in Crystals

- Ultrashort radiation pulses < λ_p
- Ultrashort drive charge < λ_p
- Resonant excitation by Xrays



Tajima,Cavenago, PRL 59 (1987), 1440

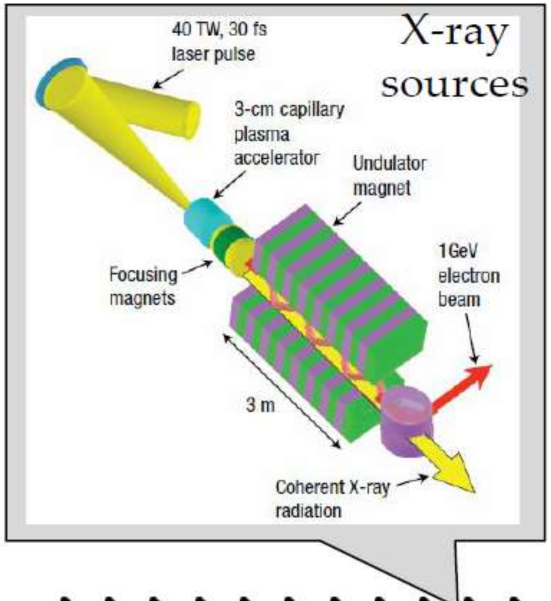
FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

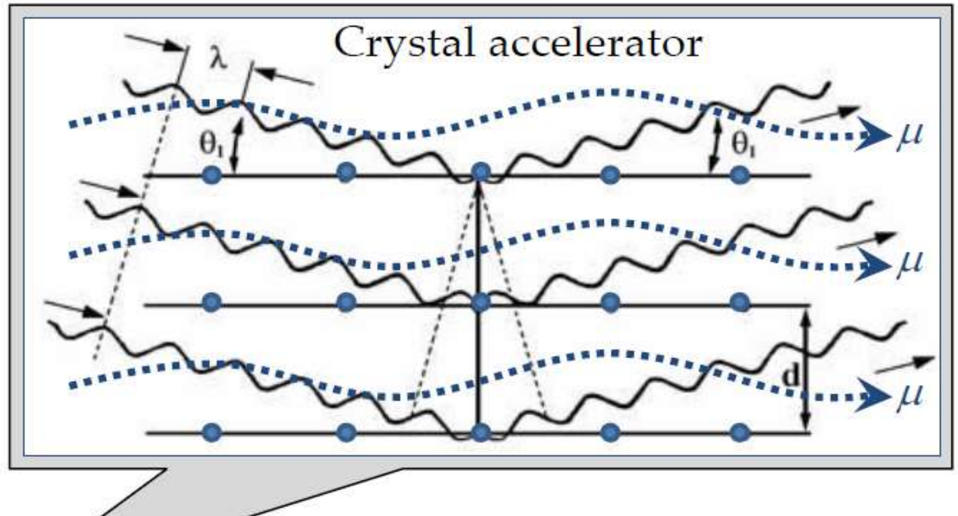
Linear $\mu^+\mu^-$ Crystal X-ray Collider

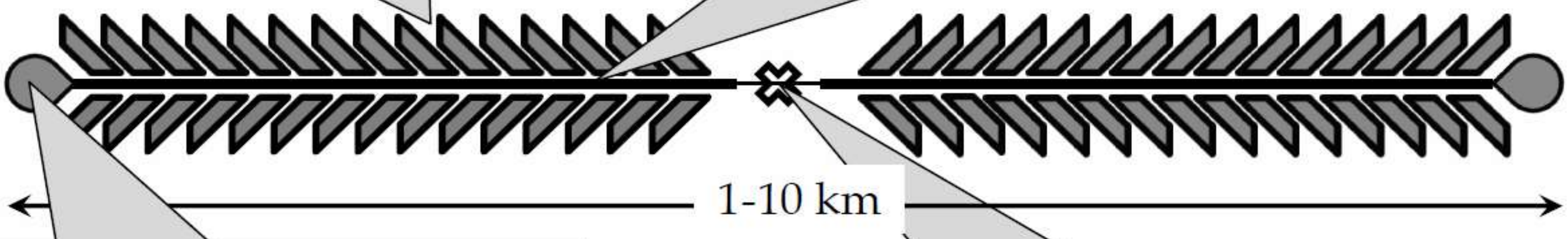
V.Shiltsev, Physics-Uspekhi 55 (10), 965 (2012)

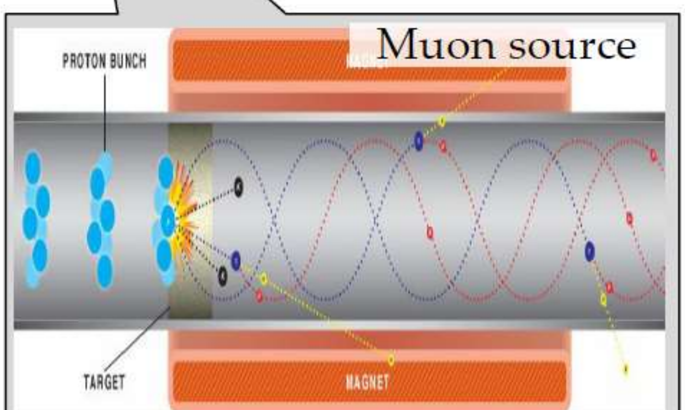
1 PeV = 1000 TeV

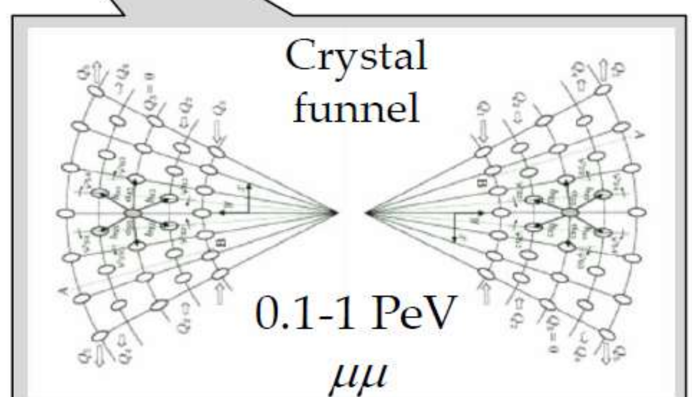
n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~$10^{30\text{-}32}$





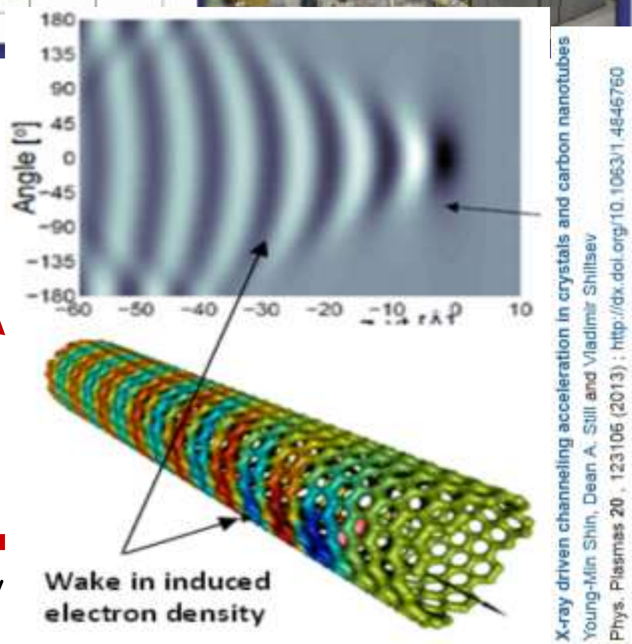






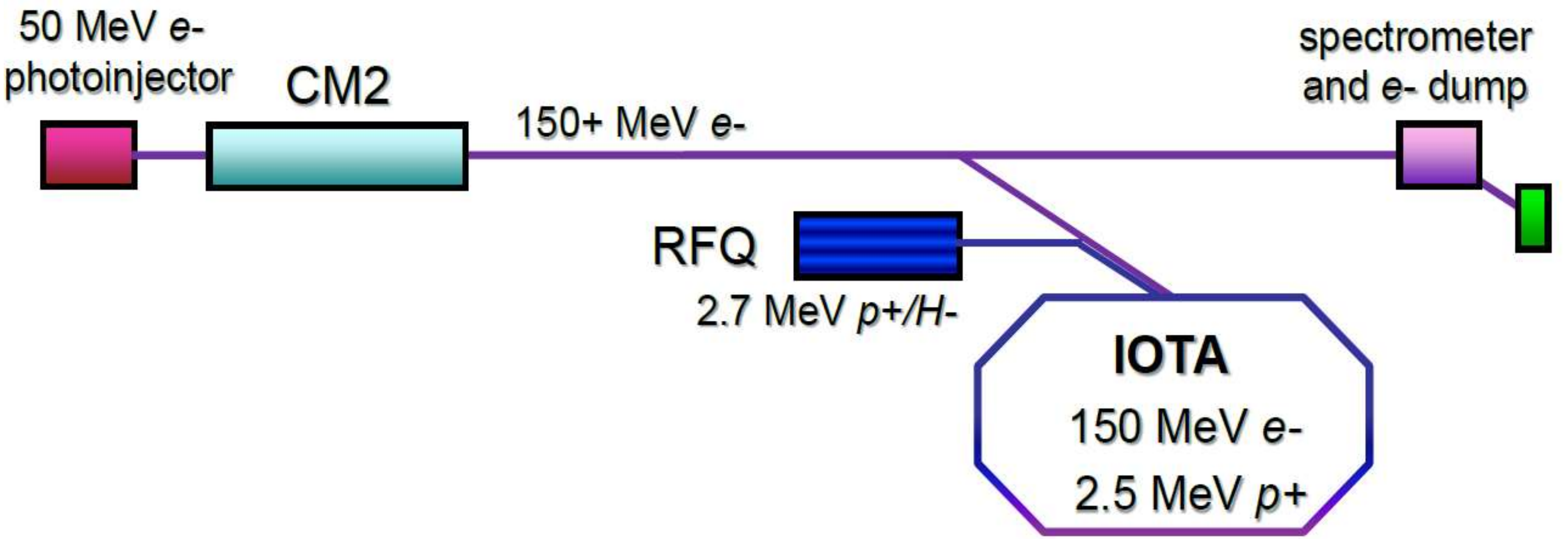
The Value of R&D Facilities

- Really critical
  - not much can be done at operational accelerators
  - Bring new people & ideas
- Acceleration in crystals
  - Or in carbon-nano-tubes C
  - can be done at LCLS or AS
- "Crystal funnel"
  - can be done with p's at MTest
  - with muons – at ASTA

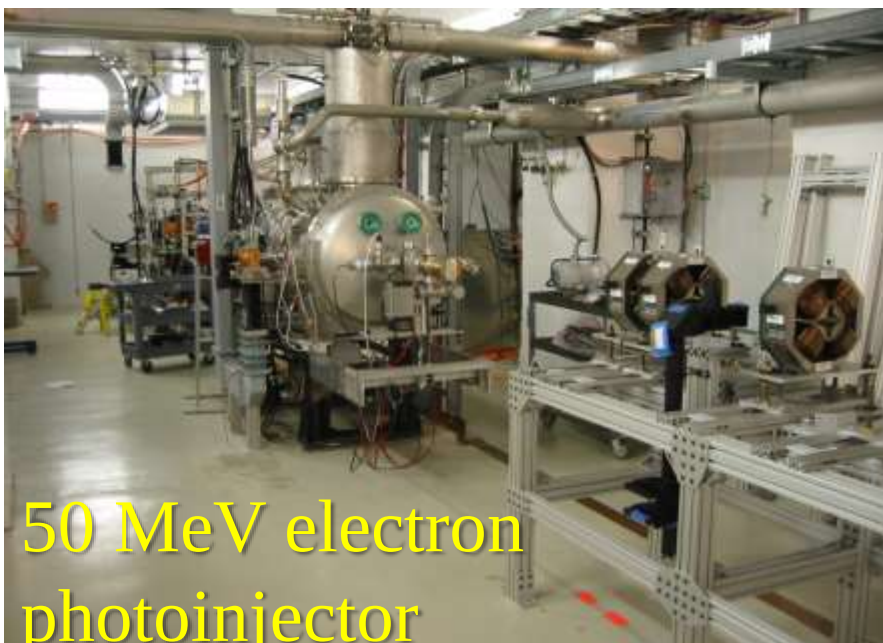


Advanced Superconducting Test Accelerator (ASTA) at FNAL:

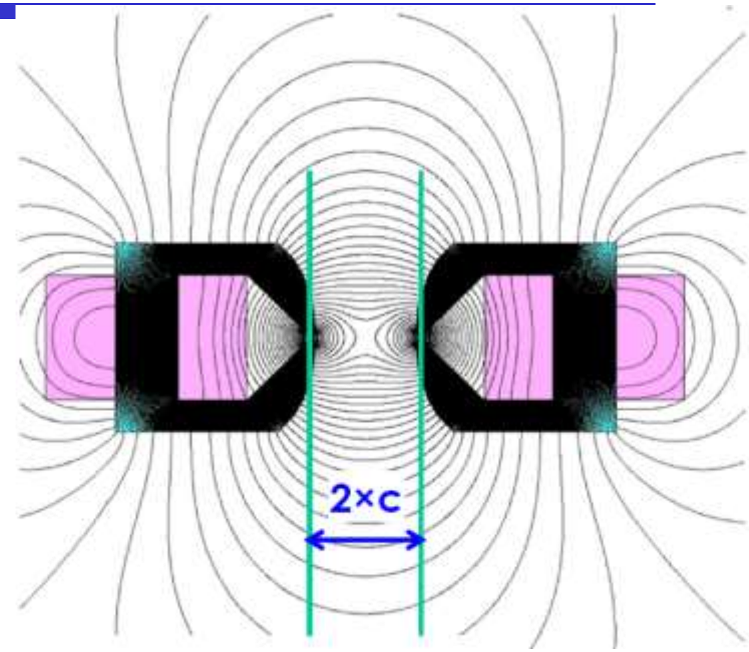
for Accelerator R&D on photoinjectors, SCRF e- linacs, proton rings, space-charge compensation, integrable optics, acceleration in crystals and carbon nanotubes, proton halo, etc, etc, etc



ASTA Facility at Fermilab

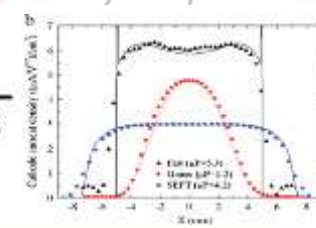


Integrable Optics Concept

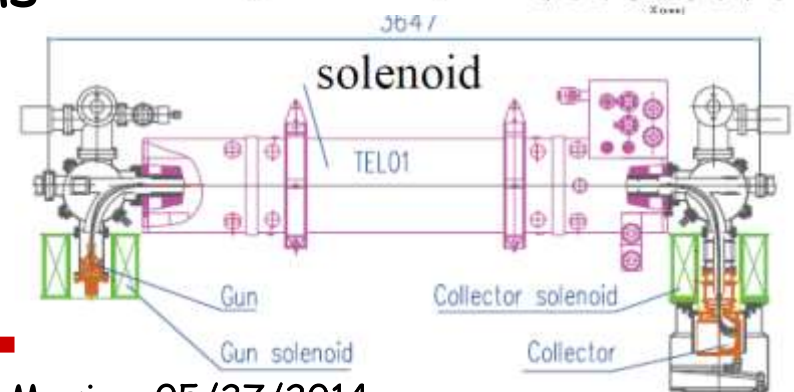


- "Integrable Optics" solutions:
  - ➢ Make motion limited and long-term stable (usually involves additional "integrals of motion")
- Can be Laplacian (with special magnets, no extra charge density involved)

$$n(r) \propto \frac{I}{\left(ar^2+1\right)^2}$$



- Or non-Laplacian (with externally created charge –e.g. special e-lens *E(r) ~r/(1+r^2)*
- *Effect is fascinating*



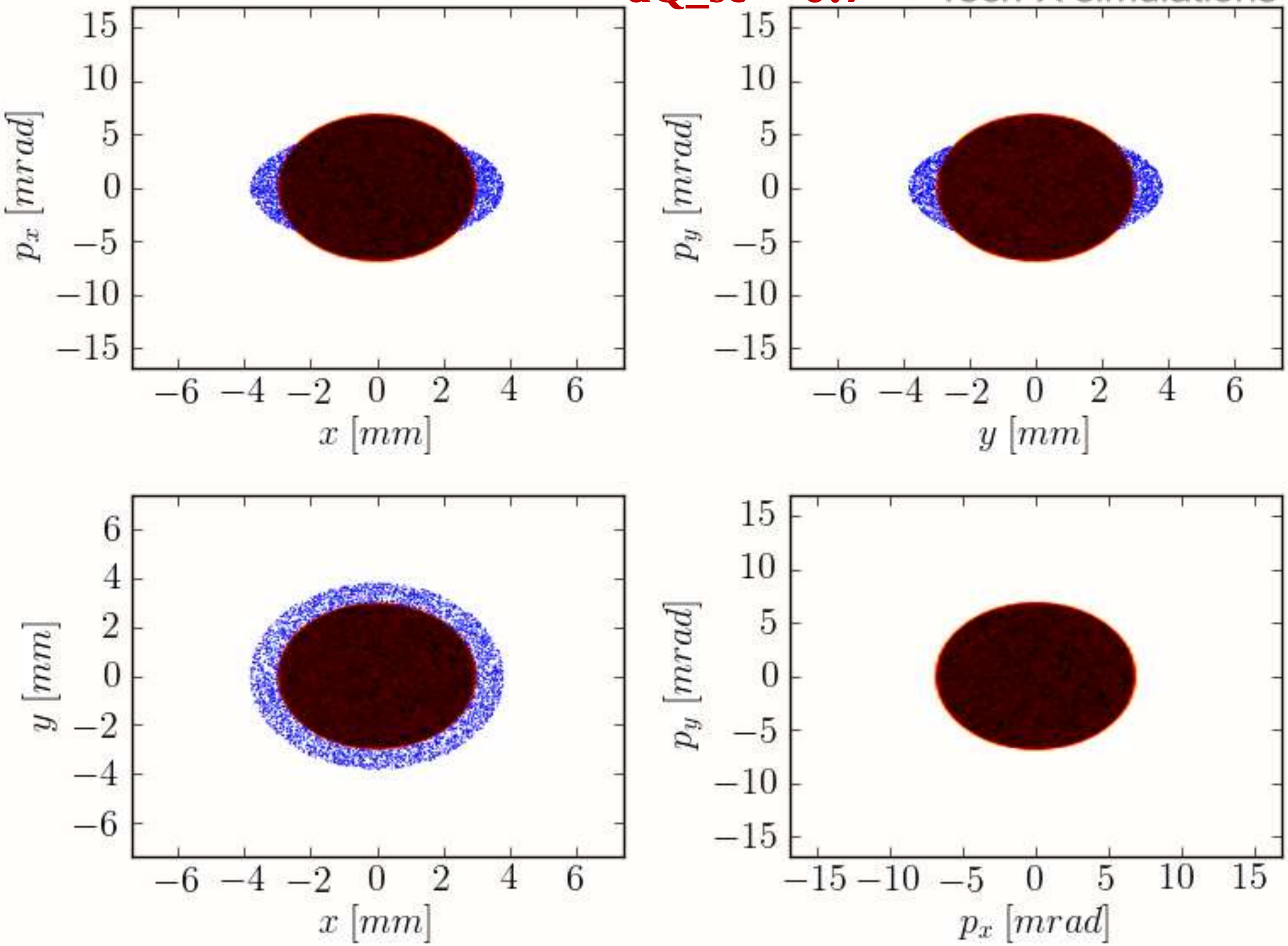
Space Charge Effects in Linear Optics Ring

System: linear FOFO; 100 A; linear KV w/ mismatch

Result: quickly drives test-particles into the halo

dQ_sc ~ 0.7

Tech-X simulations



500 passes; beam core (red contours) is mismatched; halo (blue dots) has 100x lower density

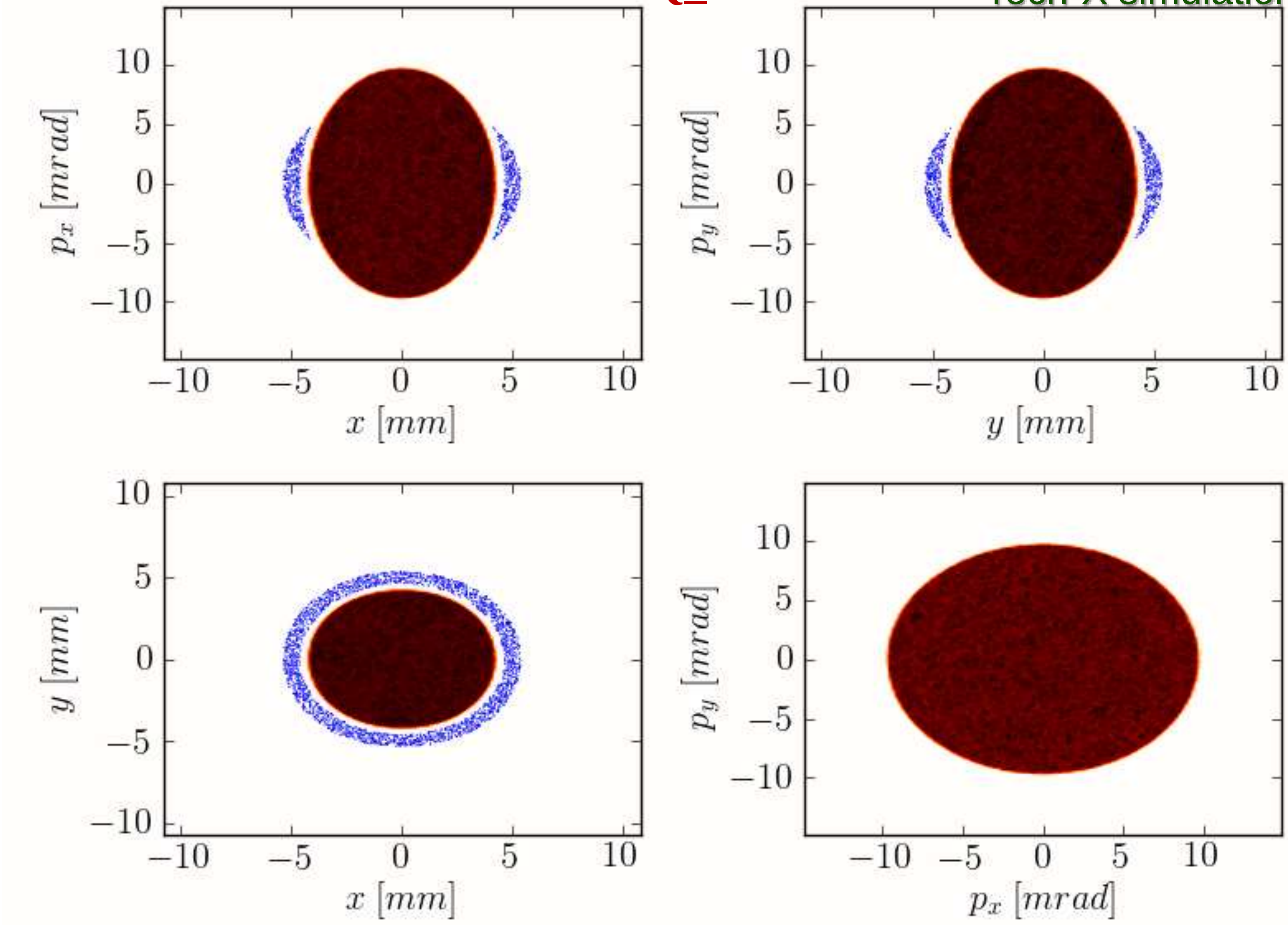
Integrable Optics Ring with Space Charge

System: octupoles; 100 A; generalized KV w/ mismatch

Result: nonlinear decoherence suppresses halo

dQ_sc ~ 0.7

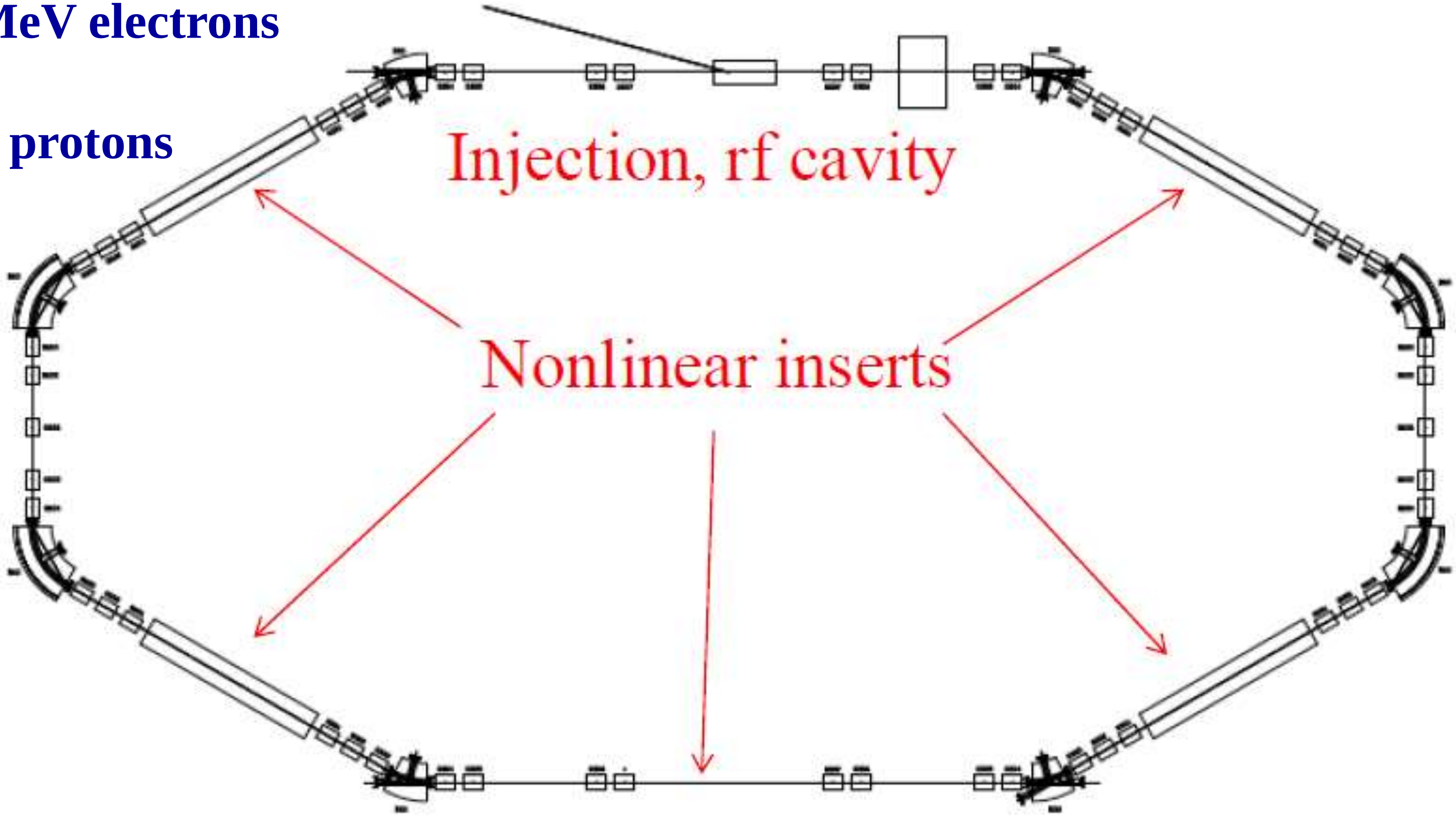
Tech-X simulations



500 passes; beam core (red contours) is mismatched; halo (blue dots) has 100x lower density

Integrable Optics at IOTA ring @ASTA

50-150 MeV electrons
C=38 m
2.5 MeV protons (later)



- Main goals for studies with pencil electron beam:
  - Demonstrate a large tune shift of ~1 (with 4 lenses) without degradation of dynamic aperture (minimum 0.25)
  - Quantify effects of a non-ideal lens and develop a practical lens (m- or e-lens)

Summary on Accelerators and R&D

- **Colliders - success:**
  - **29 built over 50 yrs, ~10 TeV c.m. achieved**
  - **Next energy frontier colliders will depend on LHC results and R&D**
- **Neutrino physics – many challenging issues:**
  - **require high power, low cost accelerators → need R&D**
- **To progress the world of particle physics requires:**
  - **Physicists (professors, students, researchers)**
  - **Good ideas and advanced technologies**
  - **Accelerator R&D beam facilities for various users**
- **Fermilab is offering several facilities, including the most modern one - ASTA - and:**
  - **We want you to come!**
  - **There are already many ties between Mexican groups and Fermilab – it's time for Accelerator S&T**

Int’l Collaboration Programs in Accelerator S&T at Fermilab

- Japan (since 1979)
- Italy (1984)
- Russia (1999)
- India (2003)
- Korea (2012)
- Turkey (2014)
- (Mexico - ?)

- Variety of forms
- Many areas

Programs/Forms of Collaboration

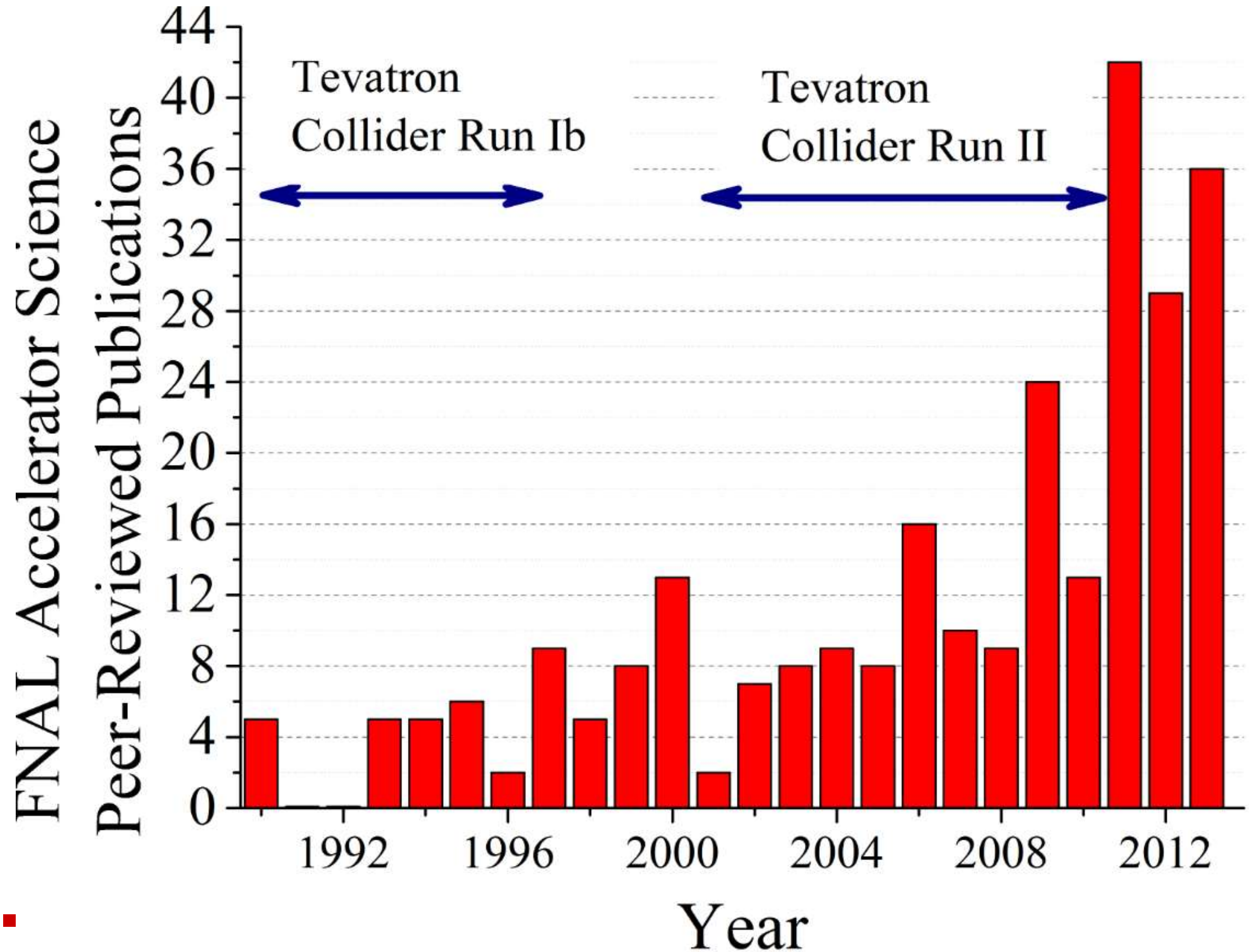
- US Particle Accelerator School
  - 2 weeks, twice a year
- Internships:
  - Summer programs, longer term programs
- Collaborations:
  - On many topics – from magnets, sources, to beam dynamics
  - Guests, visitors
- Fermilab's Accelerator PhD Program:
  - Need University professor
  - Support full/partial research (only)
- Fellowships:
  - Peoples (sci), Bardeen (engineers), Toohig (US LARP)
- Grants:
  - eg, in USA – grants from DOE, NSF, Universities

Yet another reason to come to Fermilab -

- Fermilab's *Futbal* League &Team (~1/2 from Latin America, 4 from Mexico)

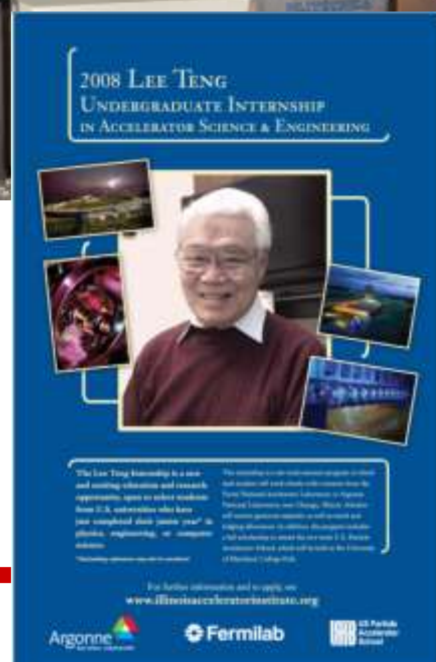
Gracias por su atención!

Back up slides


FNAL Accelerator Science
Peer-Reviewed Publications
Tevatron
Collider Run Ib
Tevatron
Collider Run II
44
40
36
32
28
24
20
16
12
8
4
0
1992
1996
2000
2004
2008
2012
Year

ASTA and USPAS, Lee Teng Internship

United States Particle Accelerator School



- USPAS sees opportunity for a number of hand-on, practical training laboratory sessions at ASTA :
  - Modern RF systems class
  - Beam Instrumentation Lab
  - Fundamentals of Accelerator Instrumentation
  - Beam Measurements and Diagnostics in Linacs and Rings
  - Beam Dynamics Experiments at the IOTA ring
  - Beam Measurements, Manipulation and Instrumentation in SCRF Linac
- Similarly, one week training sessions can be set up for Lee Teng Interns (ANL-Fermilab Undergrad Program)
- Same will be offered for ~dozen existing educational institutions with Accelerator Science curriculum – as none has capability to operate such a complex

U.S.-Japan collaboration in high energy physics

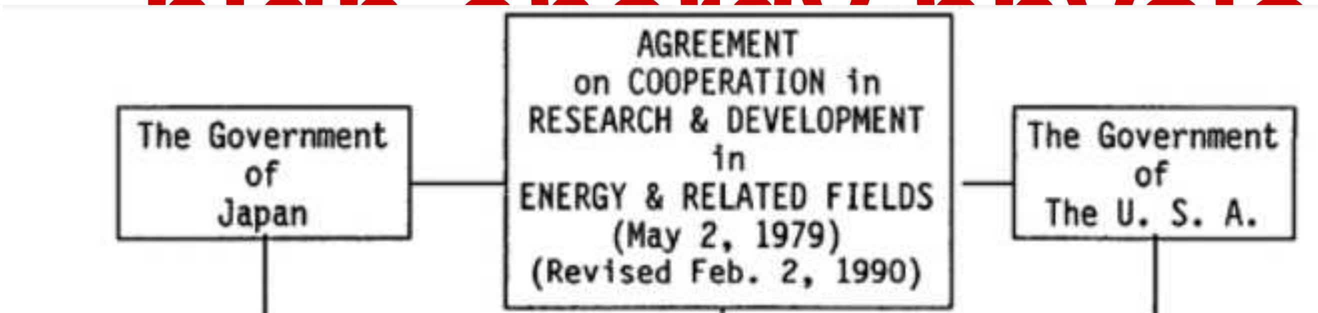
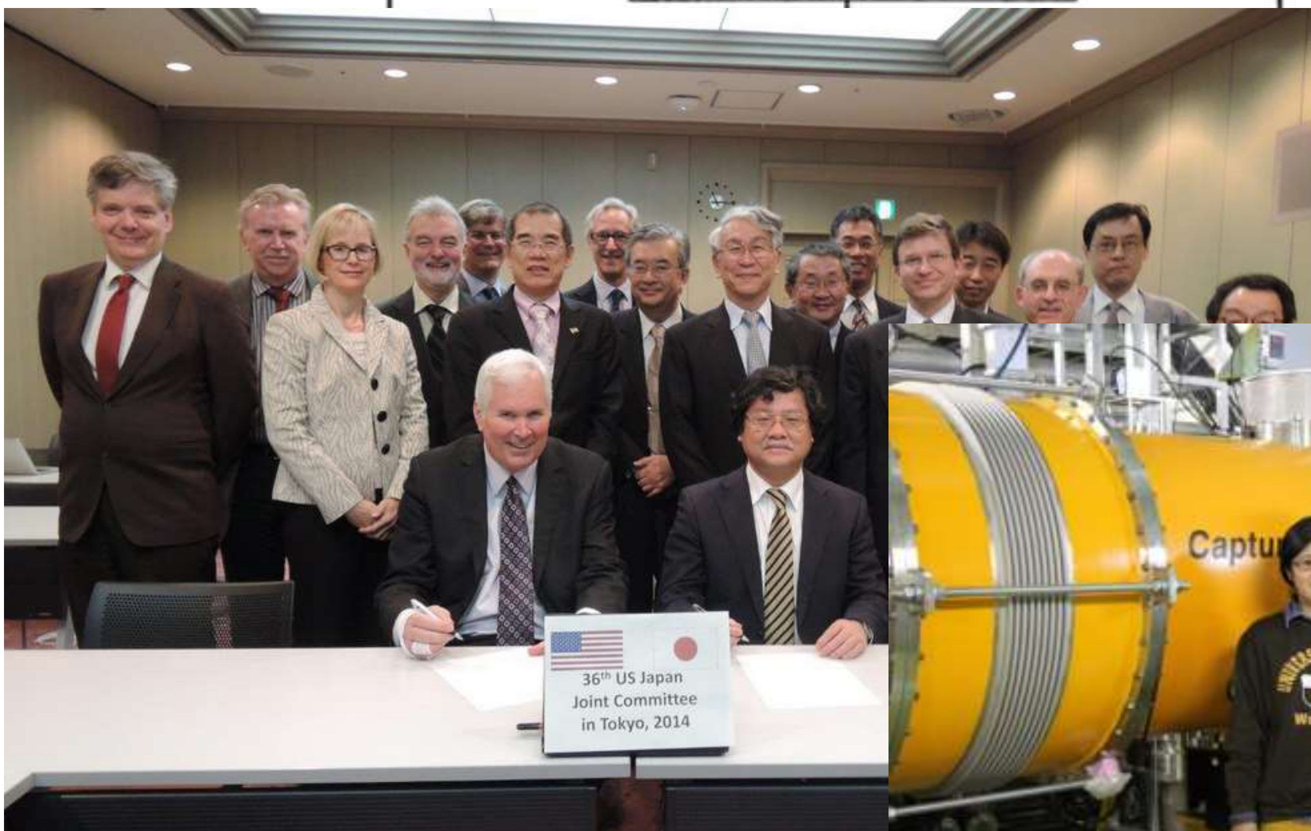


Fig. 1. Scheme of the US/JAPAN Coop



Korea-US Collaboration Center for Accelerator Science at Fermilab (2012)

ceremony of the KUCC was attended by Yul-Rae Cho, second Vice Minister of the Ministry of Education, Science and Technology; Dr. Sun-Kee Kim, Director of the Rare Isotope Science Project; Dr. Pier Oddone, Director of Fermilab; and Dr. Young-Kee Kim, Deputy Director of Fermilab.

o dispatch roughly ten young researchers every year to US accelerator laboratories to secure the specialised skills necessary for the development of the heavy-ion accelerator in Korea

Summer Internships

Fermilab | U.S. DEPARTMENT OF ENERGY

Home | Programs | Key Dates | Contacts | Mentors | Faculty | Lectures | Tours | Former Interns | About Fermilab

Internships for Italian Students (INFN, DOE, SSSA, ISSNAF, CAIF)

Program Description

Each year the Italian Istituto Nazionale di Fisica Nucleare (INFN), the U.S. Department of Energy (DOE), Scuola Superiore (SSSA), the Italian Scientists And Scholars in North America Foundation (ISSNAF) and the Cultural Association of italians at Fermilab (CAIF) offer a number of nine-week summer research internships in science, engineering and technology for highly motivated Italian physics and engineering university students. In these comprehensive programs, students work with scientists or engineers on projects related to Fermilab's research program or in similar programs at similar U.S. institutions. They also attend career planning and numerous training/informational sessions.

Support includes:

- Weekly student stipend
- Shared housing
- Shared use of a rental car
- Transportation to join the program and return home or to school for students living outside the Fermilab area

Eligibility

- Students must be at least 21 years old.
- No requirement on nationality; non-Italian students may apply.
- Students must be physics or engineering majors.
- Participants must provide evidence of identity and eligibility to work in the U.S.
- Participants must have medical insurance while at Fermilab.

Key Dates

Check Key Dates.

Expectations

- Complete the full nine-week program.
- Complete all Fermilab safety and computing requirements.
- Work safely in a responsible and professional manner.
- Attend all scheduled events including lectures, tours and group activities.

Deliverables

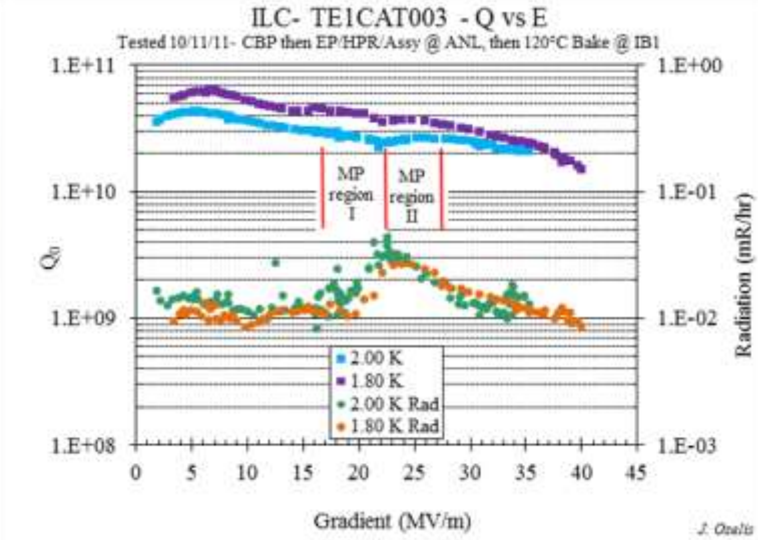
- Complete entrance and exit surveys.
- Give a final presentation to mentors and peers.
- Submit a research paper or PowerPoint presentation.
- Submit a research abstract in the required format.

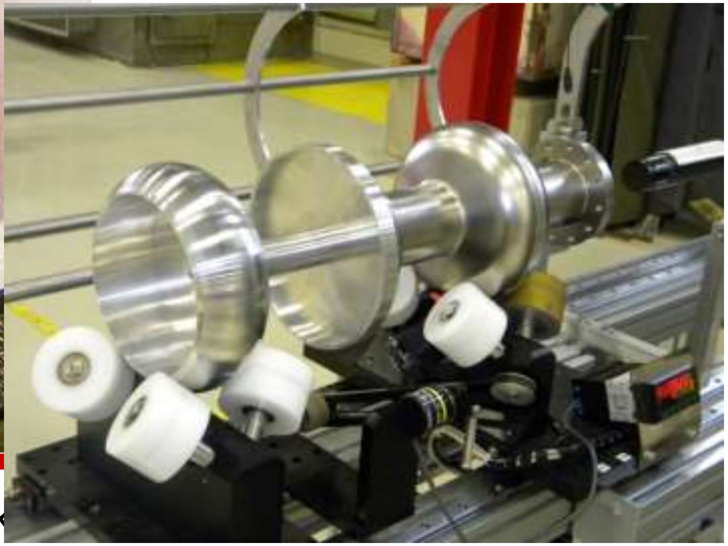
Check out the students from previous years and the 2012 Students.

Year	Applied	Accepted	INFN	SSSA	ISSNAF	#Physics	#Engineer
2008	60	20	14	6	-	12	8
2009	60	22	18	4	-	9	13
2010	230	24	18	2	4	16	8

Indian Institutions – Fermilab Collaboration

- (Since 2003)
- 2010 boost on SRF





Summer Internships | Fermilab | U.S. Department of Energy

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Physics of Accelerators and Related Technology for International Students (PARTI)

since 1999

- Программа принимает до 10 студентов из бывш Советского Союза на 3 летних месяца (физика, инженерия, вычи)
- 5 студентов в программе *PhD in Accelerator Physics* – 3-4 года в Фермилабе и защита в России

ICAS(Russia) students at Fermilab

Sponsored by Russian Ministry of Education and Science

Irina Petrushina (Moscow Engineering Physical Institute) studies superconducting RF cavities under Dr. Nikolai Solyak (FNAL)

Italian Summer Students: 2008-2013

Year	Applicants	Accepted	INFN and FNAL groups	SSSA	ISSNAF	#Physicists	#Engineers
2008	60	20	14	6	-	12	8
2009	60	22	18	4	-	9	13
2010	230	24	18	2	4	16	8
2011	100	27	18	4	5	19	8
2012	110	21	12	5	4	10	11
2013	100	22	15	4	3	11	11

- Students were from University of Pisa, Roma, Padova, Siena, Trieste, Trento, Bologna, Torino, Naples, Sant'Anna Engineering School of Pisa, Polytechnic of Turin, Polytechnic of Milan, and Order of the Engineers of the Italian Provinces

Italians at Fermilab - Class of 2012

Beam Cooling

- Tertiary production of muon beams
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
    - dE/dx energy loss in materials
    - RF to replace p_{long}

The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations